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STRATIGRAPHY OF THE KNIFE LAKE SERIES IN THE KEKEQUABIC-OGISHKEMUNCIE AREA, MINNESOTA

BY J. T. STARK AND V. G. SLEIGHT

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ABSTRACT

Detailed studies of the "Knife Lake series" in the Vermilion district of northeastern Minnesota in the vicinity of Kekequabic and Ogishkemuncie lakes reveal two series of continental sediments separated by an unconformity of considerable magnitude. The sediments of the Knife Lake series, in contrast to the Lower Huronian series of the south shore of Lake Superior, are a more continental than marine type, more intensely folded, and are metamorphosed by intrusions of Algoman granite. The unconformity within the Knife Lake series adds one more contrasting feature to those previously described and supports the revised correlation by Leith, Lund, and Leith (1935) that "in the absence of proved age relations it seems undesirable that terms like 'Huronian' should be extended to include beds representing such contrasting types of sedimentation." However, nothing in the present study suggests that the Knife Lake series is older than the Eparchean interval.

INTRODUCTION

The Knife Lake sedimentary series in the Vermilion iron district of the Lake Superior region is well exposed in the vicinity of Kekequabic and Ogishkemuncie lakes, about 40 miles northwest of the town of Ely,

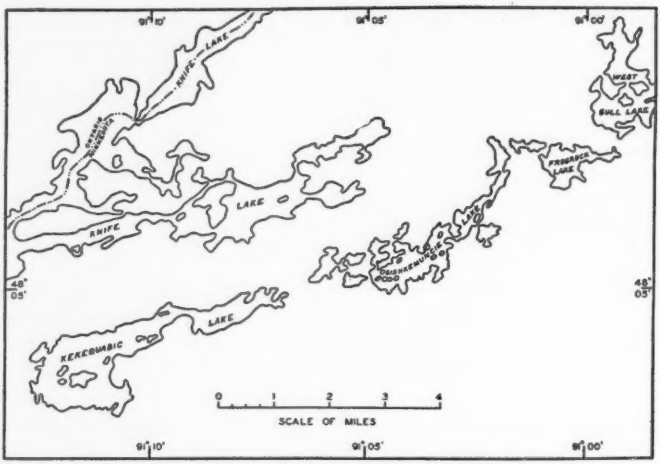

FIGURE 1.—*Sketch map of the Kekequabic and Ogishkemuncie lakes area*

Minnesota, and just south of the International Boundary (Fig. 1). Although the area in question represents but a small portion of the entire exposure of the Knife Lake series (less than 30 square miles) detailed studies have revealed new features of the stratigraphy which justify their description for record. A progress report was made in 1931 before the Geological Society of America (Grant and Stark, 1931, p. 241), and the final results are now summarized.

The area was mapped before 1901 by members of the Geological and Natural History Survey of Minnesota and reported upon by Clements (1903) and by Van Hise and Leith (1911). Detailed mapping of the Kekequabic area was done by Grant in 1893, while he was a member of the Minnesota Survey. Work by the writers was started under Professor Grant in 1924 and continued through several summers. Repeated visits have been made to the area with parties from Northwestern University, and acknowledgment is made to the many students for their aid in the field. Appreciation is here expressed to Professors C. K. Leith, F. F. Grout, and J. W. Gruner who at various times visited Northwestern parties in the field and gave generously of their time and intimate knowledge of the region.

REGIONAL RELATIONS

Sedimentary formations mapped previously as Lower-Middle Huronian lie unconformably above the Archean complex of greenstone and reflect, in their general strike of N. 55° to 60° E., the regional structural trends.

TABLE 1.—*Sequence of rock formations on the Vermilion Range*
After Leith, Lund, and Leith (1935)

PRE-CAMBRIAN	ALGONKIAN TYPE	KEWEENAWAN	DULUTH GABBRO
		UPPER HURONIAN	ROVE SLATE
		MIDDLE HURONIAN	UNC ? GUNFLINT IRON FORMATION
		LOWER HURONIAN	UNC
		ALGOMAN GRANITE	VERMILION GRANITE
		KNIFE LAKE (MAY BE LOWER HURONIAN)	KNIFE LAKE SLATE: SLATE; AGAWA IRON-FORMATION MEMBER; OGISHKE CONGLOMERATE
			UNC
	ARCHEAN TYPE	LAURENTIAN	GRANITE
		KEEWATIN	SOUDAN IRON FORMATION ELY GREENSTONE

Northward dips range from 60 degrees to vertical. Locally the Knife Lake slates are closely folded and overturned. A wide fault zone traverses the eastern half of the area, striking in general N. 35° to 45° E., along the south-central and eastern part of Ogishkemuncie Lake. A throw of at least 4800 feet is involved. Many faults with small horizontal offsets cut the formations and are later than the Keweenawan basic dikes which are numerous throughout the area (Stark, 1927, p. 283-286; Sleight, 1933, p. 57-67).

STRATIGRAPHIC SEQUENCE

GENERAL CONSIDERATIONS

Since the geology of the Vermilion district has been described by many writers (Clements, 1903; Van Hise and Leith, 1911; Leith, Lund, and Leith, 1935), only a brief summary is necessary here. The sequence of rock formation, as given by Leith, Lund, and Leith (1935), is shown in Table 1. A detailed section of the Knife Lake series and related formations is given in Table 2, based on the work in the Kekequabic-Ogishkemuncie area. The approximate thicknesses of the sedimentary forma-

tions refer specifically to the Ogishkemuncie area. The character of the sedimentary formations is somewhat modified in the Kekequabic area by large amounts of water-laid tuff and agglomerate.

TABLE 2.—*Sequence of rock formations in the Kekequabic and Ogishkemuncie lakes area*

PRE-CAMBRIAN	ALGONKIAN TYPE	UPPER HURONIAN	ROVE SLATE 1500+		
			UNC ?		
		MIDDLE HURONIAN	GUNFLINT IRON-FORMATION 300+		
		LOWER HURONIAN			
			UNC		
		ALGOMAN ?	VERMILION AND KEKEQUABIC GRANITES		
		KNIFE LAKE SERIES	KNIFE LAKE SLATE	TUFF AND AGGLOMERATE IN KEKEQUABIC AREA ARGILLITE AGAWA IRON-FORMATION MEMBER TUFFACEOUS SLATE AND GRAYWACKE	1000+
			OGISHKE GROUP	ZETA LAKE CONGLOMERATE 1000 WEST GULL CONGLOMERATE 1700 PEEBLES CONGLOMERATE 2100	
			UNC		
			DIKE LAKE SLATE 1000 MOOSE LAKE CONGLOMERATE 1700		
			UNC		
	ARCHEAN TYPE	LAURENTIAN	TOWNLINE LAKE GRANODIORITE AND SAGANAGA GRANITE		
		KEEWATIN	SOUDAN IRON FORMATION 160+ ELY GREENSTONE 1000+		

KEEWATIN

The oldest formation—the Ely greenstone—is exposed in the south-central and eastern parts of the Kekequabic-Ogishkemuncie area (Fig. 4). It is composed of a thick series of metamorphosed lava flows with inter-

calated sediments. In most outcrops ellipsoidal structures are not easily recognized, but careful examination usually reveals partly obliterated outlines of ellipsoids and spherulitic structures which are so prominent in the formation in other parts of the Vermilion district. Microscopically it resembles the Archean greenstone of the type locality at Ely, Minnesota.

In the Knife Lake area, north of Kekequabic Lake, Gruner (1929, p. 180-187) has described a belt of ellipsoidal greenstone, previously mapped as Archean, truncating Knife Lake slates which show by primary structures their younger beds toward the greenstone. Whether there is an unconformity, with younger greenstones above Knife Lake slate, or whether the relationship is due to faulting is still questionable (J. W. Gruner: personal communication to the junior author). No evidence indicating greenstone younger than Keewatin was found in the Kekequabic-Ogishkemuncie area.

SOUDAN IRON FORMATION

The Soudan iron formation, stratigraphically near the top of the Ely greenstone, is preserved only in troughs of closely folded synclines. There are no outcrops in the Kekequabic-Ogishkemuncie area, but pebbles and boulders up to 1 and 2 feet in diameter are abundant in one of the conglomerates which overlies the greenstones. These fragments consist of thinly banded and extremely contorted beds of red jasper, black chert, and white quartz. They appear identical in hand specimen and thin section with outcrops of the Soudan iron formation in other parts of the Vermilion district.

SAGANAGA GRANITE AND TOWNLINE LAKE GRANODIORITE

The Laurentian Saganaga granite batholith borders the Ogishkemuncie area on the northeast. It does not crop out in the area discussed, unless a small mass of granodiorite cutting the Ely greenstone on the Townline Lake portage (NW¼ sec. 18, T. 65 N., R. 5 W.) be considered an offshoot from it. The eastern continuation of the granodiorite is cut off by the large fault zone, and at no place has the intrusion been found cutting Huronian sediments.

KNIFE LAKE SERIES

Saddlebag Lake conglomerate.—At the base of the Knife Lake series and resting unconformably on the Ely greenstone is a basal conglomerate composed almost entirely of greenstone fragments in a schistose matrix of greenstone debris.[1] The conglomerate is well exposed along the south

[1] The name Saddlebag Lake has been given to this conglomerate by the junior author from the large exposures on the shores of Saddlebag Lake in sec. 13, T. 65 N., R. 6 W.

shores and on several islands in Ogishkemuncie and Dike lakes and irregularly around the shores of Frog Rock (Jasper) Lake.

The relationship of the conglomerate to the underlying parent greenstone is shown in many outcrops where there is apparent gradation from the weathered zone of the ellipsoidal greenstone upward into conglomerate. Other outcrops are so thoroughly schistose that outlines of pebbles and boulders are almost completely obliterated. Superficially the conglomerate looks like the greenstone, and only by finding traces of bedding in the greenish graywacke marking the upper part of the conglomerate is the sedimentary origin recognized. In earlier reports the conglomerate was mapped with the Ogishke conglomerate as part of the basal member of the rocks then supposed to be Lower-Middle Huronian (Clements, 1903, p. 284).

Dike Lake slate.—The Saddlebag Lake conglomerate is overlain conformably by a finely banded and laminated slate containing numerous beds of graywacke and lenses of black, cherty slate. The prominence of the slate around Dike Lake has suggested its name. It is also well exposed in outcrops along the northern shores and on islands of Ogishkemuncie Lake. The formation is similar to greenish and black facies of the Knife Lake slate, and the resemblance is further emphasized by the pyroclastic composition revealed under the microscope. A band of graywacke in the upper part of the slates may be followed for more than a mile from its lenslike termination against the fault zone near the center of Ogishkemuncie Lake westward to its truncation by the overlying Ogishke conglomerate at Dike Lake. West of Dike Lake, in the Kekequabic area, the lower series (Saddlebag Lake conglomerate and Dike Lake slate) is completely cut out, and the Ogishke conglomerate rests directly on the old greenstone complex southeast of Kekequabic Lake. The monoclinal structure of the Dike Lake slate formation is shown by excellently developed gradation of grain and truncated cross-bedding in all of the graywacke and coarser-grained slate bands. Tops of beds are invariably to the north. The persistence of these structures is striking throughout the Saddlebag Lake conglomerate and the Dike Lake slate and leaves no doubt as to the younger age of the overlying Ogishke conglomerate.

Ogishke conglomerate.—The Ogishke conglomerate in the area under discussion consists of facies so distinct in varietal character that three separate facies can be readily mapped. Each shows some lateral gradations into the other two, but there is also a rude vertical range with the Peebles or granite facies at the base, overlain by the West Gull or jasper facies, and the Zeta Lake or granite porphyry facies at the top.

All are true conglomerates with constituents ranging from small pebbles to large boulders up to 2 feet in diameter, embedded in a coarse sand and graywacke matrix. The well-sorted character and bedding of the conglomerate suggest fluvial deposition, and the varietal characters of the first two appear to be due to streams tapping outcrops of different source material. The Zeta Lake facies is a pyroclastic composed of volcanic fragments deposited in water with only slight reworking.

The Peebles facies contains a wide assortment of pebbles; 36 rock types have been recognized. The most easily recognized fragments are those of the Saganaga granite in which large blebs of quartz stand out prominently. Slate pebbles, apparently derived from the Dike Lake slate formation, are numerous. Some of these contain structures similar to those described by Gruner (1923, p. 147) as blue-green algae. Lenses of graywacke and slate are intercalated with the coarser bands of conglomerate and show excellent gradation of grain and truncated cross-bedding. In many outcrops these structures in the conglomerate and graywacke indicate that the tops of the beds are to the north, leaving no doubt that the conglomerate is younger than the Dike Lake slate. This granite pebble facies is typical of the Ogishke group in general in the Kekequabic-Ogishkemuncie area.

The West Gull facies lies between the Peebles below and the Zeta Lake conglomerate above. At the type locality on West Gull Lake, a few miles northeast of Ogishkemuncie Lake, the conglomerate is characterized by closely spaced red jasper pebbles and cobbles which appear identical in character to the outcrop of the Soudan iron formation known in exposures to the north.

In the western part of the Ogishkemuncie area the West Gull member contains lenses of the Zeta Lake member, a black granite porphyry pebble conglomerate. In the vicinity of Zeta Lake the porphyry pebbles increase until the conglomerate is composed almost entirely of pyroclastic fragments in a fine groundmass of the same black porphyry. This explosively ejected material was deposited in water and rudely stratified without much reworking. Recrystallization has so nearly obliterated outlines of the fragments that many isolated specimens appear to be massive igneous rocks.

Knife Lake slate.—Conformably overlying and interbedded with the upper part of the Zeta Lake conglomerate member are the typical Knife Lake slates. They are blue gray to black on fresh surfaces and weather to a light gray. Graywacke beds occur throughout the slates and become extremely prominent at the bottom and top of the slate formation. The slates are closely folded, and the true thickness is probably obscured

by folding and faulting not easily recognizable because of the homogeneity and lack of traceable horizons. In the area to the north Gruner (1929, p. 185) mapped about 2500 feet of Knife Lake slate. Locally, as at Kekequabic Lake, pyroclastic tuff and agglomerate, with water-laid sedimentary structures well developed, take the place of the upper graywackes.

Near the base of the Knife Lake slates, but occurring in lenses at several horizons instead of in a single definite stratigraphic position, are beds of the Agawa iron-bearing member. The lenses range in thickness from a few inches to 200 feet or more. Although in other parts of the Vermilion district chemically precipitated chert is recognized in outcrops in the Agawa, in the area here described the lenses are of clastic fragments interbedded with tuffaceous material. They now consist largely of hematite, magnetite, quartz, and chlorite, much of which is of pyroclastic origin (Stark, 1929, p. 538-541).

Kekequabic granite.—A soda-rich augite granite with syenite facies intrudes the Knife Lake series in the Kekequabic area. This granite is presumably contemporaneous with the Vermilion batholith which is usually classed as Algoman in age, although it may be later.

GUNFLINT IRON FORMATION AND ROVE SLATE

The Gunflint iron formation and Rove slate do not outcrop in the Kekequabic-Ogishkemuncie area but are in the table to complete the Vermilion sequence. In the revised correlation in Professional Paper 184, the Gunflint iron formation is placed in the Middle Huronian, following the revision on the south shore occasioned by the unconformity between the Ironwood iron formation and the overlying Tyler slates of Michigan. In the absence of definite proof of a similar unconformity between the Gunflint iron formation and the Rove slate the unconformity between them is drawn as questionable in Table 1 (Leith, Lund, and Leith, 1935, p. 10).

KEWEENAWAN INTRUSIVES

The Keweenawan Duluth gabbro borders the Kekequabic-Ogishkemuncie area on the south, and contact metamorphism has affected all of the above-mentioned formations. Diabase dikes are numerous throughout the area. They are assumed to be Keweenawan in age, although none has been traced directly into the gabbro.

UNCONFORMITY BETWEEN DIKE LAKE SLATE AND OGISHKE CONGLOMERATE

The relationship between the Dike Lake slate and the overlying Ogishke conglomerate is one of angular discordance. Along the north shore of

Ogishkemuncie Lake this unconformity may be traced for more than 3 miles. The greatest distance between outcrops is three-quarters of a mile where the contact strikes across a bay in the northeast arm of Ogishkemuncie Lake. Slate beds striking N. 55° E. are truncated by the base

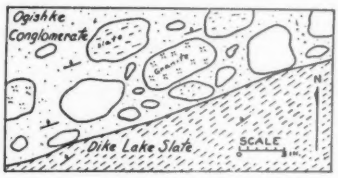

FIGURE 2.—*Sketch showing unconformity at Ogishkemuncie Lake*

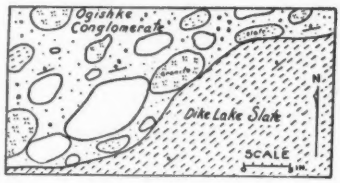

FIGURE 3.—*Sketch showing unconformity at Dike Lake*

of the Ogishke conglomerate making angles as large as 20 degrees but more commonly around 15 degrees. Figure 2 was taken as typical of 12 similar outcrops which total more than 1000 feet of exposure; it illustrates the truncation of the Dike Lake slate. At Dike Lake the angular discordance is even more pronounced. A sketch of the unconformity is shown in Figure 3.

Except for the unevenness shown in Figure 3, the erosion surface on the slates is remarkably regular. Outcrops are rarely continuous for more than a few hundred feet, but projections of the contact from exposure to exposure along the shore and islands in Ogishkemuncie Lake indicate a smooth surface. A boulder conglomerate (the basal facies of the Ogishke conglomerate) with cobbles commonly 6 to 12 inches in diameter rest on the truncated surface of the fine-grained, laminated slates. There is no suggestion of interfingering lenses, and the truncated contact extends the entire length of the lake as shown in Figure 4. The cobbles and pebbles show a wide variety of rock types, among which boulders of the Saganaga granite are easily recognized by the characteristic large blebs of quartz. Boulders of this size, which rest without distortion on the underlying slates, suggest that the original muds were probably indurated to a high degree and possibly metamorphosed to slates before torrential waters deposited the heavy boulder conglomerate.

The smoothness of the line of contact between the slate and conglomerate suggests that planation had reached a late stage to produce a surface which, for 3 miles at least, was without conspicuous difference in elevations (Fig. 4). This interpretation implies a time interval of considerable magnitude to allow induration of the Dike Lake sediments and peneplanation, locally at least, to produce such a surface.

The possibility that the strikingly smooth surface might represent an

ice-scoured pavement and that the unconformity might correlate with glaciation at the close of the Lower Huronian was considered. Such an interpretation would put the overlying Ogishke conglomerate and Knife

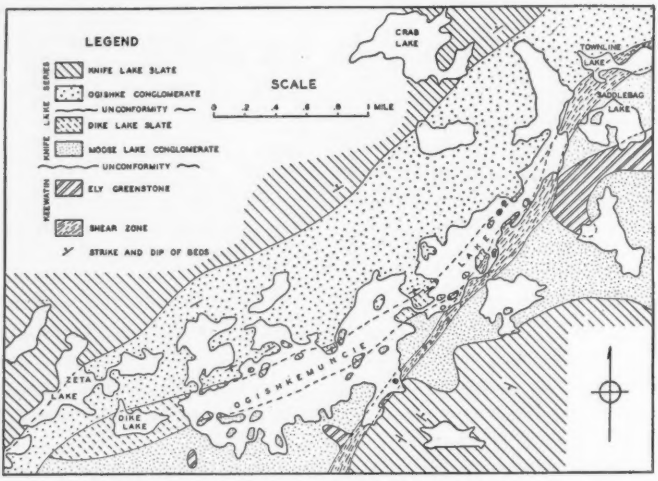

FIGURE 4.—*Geologic map of Ogishkemuncie Lake area*

Lake slate in the Middle Huronian and assign the Dike Lake slate and Saddlebag Lake conglomerate to possibly Lower Huronian. Against this is the failure to find, in any part of the Ogishke conglomerate, any striated or markedly subangular fragments, such as characterize glacial deposits. Laminations in the Knife Lake slates were carefully but unsuccessfully examined for glacial varves. One 3-foot block of banded slate, presumably from the Dike Lake formation, was found isolated as an erratic in the Knife Lake slates, suggesting possible ice rafting. In the absence of any clear evidence of glacial scour and deposits, however, planation by running water is considered the more likely explanation, and the high degree of smoothness is thought to indicate an erosion interval of more than slight significance. None of the exposures show evidence of interfingering of the Dike Lake slate with the Ogishke conglomerate. Such evidence would prove the break to be of no significance.

AGE OF THE KNIFE LAKE SERIES

To the troublesome question of the correlation of the Knife Lake series the foregoing discussion of a small section of that series adds a detailed section which may be of local importance only. The chief con-

tribution, however, has been the description of the new unconformity and the division of the Knife Lake series into a lower (Saddlebag Lake) conglomerate and (Dike Lake) slate separated by an angular unconformity from the overlying Ogishke conglomerate and Knife Lake slate.

The problem of age of the Knife Lake series and alternative correlations are well summarized by Leith, Lund, and Leith (1935, p. 16-17) and in the recent paper by Pettijohn (1938). The Knife Lake slates may be Lower Huronian or they may be pre-Lower Huronian and possibly equivalent to the Timiskaming. Against the first possibility is the dissimilarity between the marine sediments of the Lower Huronian of the south shore of Lake Superior and the continental, and commonly pyroclastic, Knife Lake series. Objections to calling them pre-Huronian are the implications that such a correlation would put formations which are not Archean in type below the Eparchean interval and that this grouping obscures the major unconformity known to exist above the basement complex of greenstone (Leith, Lund, and Leith, 1935, p. 17).

Commenting on the use of Huronian as a term descriptive of rock type, Dickey (1938a, p. 419-420) raised the question as to the future utility of the designations Lower, Middle, and Upper Huronian, since they refer to stratigraphic position.

> "If, for instance, further investigation reveals . . . the existence of a sequence of Huronian type unconformably below the base of our present Lower Huronian, and if so, how shall we refer to our present Lower and Middle Huronian?"

Such a contingency now arises in the Kekequabic-Ogishkemuncie area. Whether the Knife Lake slate and Ogishke conglomerate be considered Lower Huronian or older, we now have the presence of Dike Lake slate and Saddlebag Lake conglomerate indicating the existence of a sequence of Huronian type unconformably below the Ogishke conglomerate.

The assumed absence of Algoman granites on the south shore of Lake Superior and the lack of positive proof that the Vermilion batholith and associated intrusions (*e.g.*, Kekequabic granite and Snowbank granite) are Algoman in age and not younger further complicate the problem. Recently Dickey (1938b) has cited evidence that in the Ford River area of Michigan granite intrusions are post-Lower Huronian and pre-Middle Huronian; he suggests the possibility of the Ford River granite being a correlative of the Algoman granite of the north shore of Lake Superior.

Pettijohn (1937, p. 190-192) has argued for a diversity of ages or a fourfold division for the pre-Cambrian of the north shore, placing the Knife Lake series in division III (Pettijohn) of the Early pre-Cambrian, below the Eparchean interval, but separated in turn by a major unconformity from the underlying divisions II and I. This would avoid the use of the embarrassing term Huronian. The unconformity within the

Knife Lake series lends support to an increasing diversity of ages for the pre-Cambrian and fits in with Pettijohn's proposed revision for correlation of the northern subprovince of the Lake Superior region.

In accord with Leith, Lund, and Leith, until age relations have been proven it seems desirable to continue the use of noncommittal terms that will not obscure general agreement as to facts and to retain the name Knife Lake series for the pre-Gunflint and post-Archean complex of the Vermilion district. The Saddlebag Lake conglomerate and Dike Lake slate are included, temporarily, at the base of the Knife Lake series until study of additional areas brings in more rocks which can be correlated with them and substantiate or disprove the possibly great unconformity with the overlying Ogishke conglomerate.

CONCLUSIONS

The great depth to which erosion proceeded before exposing the Saganaga granite marks a major break between what Leith (1934, p. 171) defines as

> "underlying, more or less indivisible, basement complex, containing igneous and sedimentary rocks, or both, in which ordinary stratigraphic methods do not apply"

and the post-Archean formations. The Soudan iron formation was almost completely stripped from the region, leaving only narrow belts closely infolded in deep troughs in the Ely greenstone.

On this surface of profound erosion the Saddlebag Lake conglomerate and Dike Lake slates were deposited. These formations are continental and resemble closely the overlying conglomerates and slates. Lithification and erosion followed. The period of erosion was long enough to produce a strikingly flat surface suggestive of peneplanation. On the truncated edges of the Dike Lake slates the Ogishke conglomerate composed of a wide variety of rock types was deposited. The coarse fluvial sediments were overlain by thick Knife Lake slates, more or less tuffaceous throughout and especially at the bottom and the top of the formation. Locally, thick beds of coarse, water-laid agglomerate occur near the top of the slates.

The end of the Knife Lake series deposition was marked by diastrophism and intrusion of the Kekequabic (Algoman?) granite. Another major erosion interval followed before the Gunflint iron formation was deposited on the steeply dipping, truncated edges of the Knife Lake series (Howland and Thayer, 1931, p. 25). It is at this strikingly angular unconformity between the Gunflint and the Knife Lake that Collins (1937, p. 1455) and others would place the break between the Archean and Proterozoic.

The exact age of the Knife Lake series is questionable, but it seems best to classify them simply as post-Archean and pre-Gunflint until further information becomes available. The two new formations of Huronian type (the Saddlebag Lake conglomerate and Dike Lake slate) are temporarily included with the Knife Lake series as a lower unconformable portion of that great series.

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

PART I THE LACCOLITHS

BY CORNELIUS S. HURLBUT, JR. (With Section on Structure and Mechanism of Intrusion BY DAVID T. GRIGGS)

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ABSTRACT OF PART I

Nine laccoliths to the east and northeast of the Highwood Mountains are described. With one exception they have been intruded into the upper Cretaceous Eagle sandstone. Varying degrees of erosion in the different laccoliths permit some to be studied in more detail than others. Discussion centers around Shonkin Sag laccolith since it is of most general interest and is most completely exposed.

All the rocks of the different laccoliths show the same mineral assemblage; the chief difference between them is a variation in the percentages of the minerals present. The only major exception is the hornblende-sodalite syenite from the top of Square Butte. In four laccoliths a horizontal layer of syenite is present with a thick zone of shonkinite below and a thinner zone of shonkinite above. In three other laccoliths, syenite is found above shonkinite, but the upper contacts are eroded. In several laccoliths an increase in density upward through the lower shonkinite was observed. In addition to this variation, Shonkin Sag laccolith shows a decrease in density downward through the upper shonkinite.

Field and laboratory observations made on all the laccoliths are explained on a theory of differentiation in place. This theory is based on the settling of heavy crystals accompanied by minor rising of leucite in a cooling body.

INTRODUCTION

PREVIOUS WORK

Although mention of the Highwood Mountains is common in the reports of earlier explorations in the region, notes on the geology appeared first in a paper by Hayden in 1861. Brief comments are found in his later reports. In 1883 Davis (1886) and Lindgren, while working on the Northern Transcontinental Survey, crossed the Highwood Mountains through Highwood Gap, and Lindgren (1886; 1890) described some of the igneous rocks. C. A. White and J. B. Marcou visited Square Butte in 1883 and collected a sodalite syenite which was later described by Lindgren (1893).

As part of the area covered by the Fort Benton folio of the United States Geological Survey, the Highwood Mountains were mapped and studied in the field by Weed and Pirsson in the latter part of the summer of 1894. These men returned to the eastern part of the area for a few days in 1896. They published a preliminary report in 1895, in which

the general field relationships of the sedimentary and igneous rocks were outlined. In 1896 they announced the discovery of a new type of granular rock containing leucite. It was named missourite and was supposed to make up the whole mass of the Shonkin stock. The Fort Benton folio appeared in 1899. The northern end of the Little Belt range, the Highwood Mountains, and the surrounding plains are described in the text and shown on the maps (Weed, 1899). The Shonkin Sag and Palisade Butte laccoliths were the subjects of a paper by Weed and Pirsson in 1901. Both laccoliths were held to show differentiation in place (Weed and Pirsson, 1901, p. 1-17). The most comprehensive treatise on the igneous rocks of this mountain group appeared in 1905 under Pirsson's name. This memoir (Pirsson, 1905) contains data which are at variance with the preliminary report by Weed and Pirsson. These discrepancies will be pointed out where they seem pertinent to the present work. Pirsson gave megascopic and microscopic descriptions, chemical analyses, maps, and an account of the field occurrences of all of the important rock types found.

Nothing more was written on the igneous rocks of the Highwood Mountains until 1931, when a paper by Osborne and Roberts, on differentiation in Shonkin Sag laccolith, appeared (Osborne and Roberts, 1931). In April 1935 a brief preliminary report of the present work appeared (Larsen *et al.*, 1935). In December 1935 at the meetings of the Geological Society of America, Hurlbut presented a paper on Shonkin Sag laccolith. The last paper dealing with Highwood geology is an account of the Shonkin Sag laccolith by Barksdale (1937).

The glacial geology of the area has been described by Calhoun (1906) and Alden (1932), and the structure of the Cretaceous rocks by Reeves (1929).

WORK AND ACKNOWLEDGMENTS

This study of the igneous rocks of the Highwood Mountains was undertaken by a group of geologists from Harvard University, and the project was financed by a grant from the Shaler Memorial Fund of the Division of Geological Sciences of Harvard University. The group was made up of E. S. Larsen, C. S. Hurlbut, Jr., C. H. Burgess, D. T. Griggs, and B. F. Buie. The field work was begun in the summer of 1933, and during most of that summer the party worked together. Throughout the work the party cooperated closely, but in the latter part of 1933 and throughout the summer of 1934 the problems were divided. Larsen had general supervision and worked particularly on the extrusive rocks, Hurlbut and Griggs worked on the laccoliths, Burgess on the stocks, and Buie on the dikes and smaller intrusives. Buie worked in the field during the summer of 1935, and Larsen made a short visit to the field

in the summer of 1936. Hurlbut and Griggs spent 3 weeks in field work in July 1938. Larsen was assisted in the field by N. A. Haskell, Burgess by Mrs. Burgess, Hurlbut by Mrs. Hurlbut, Griggs by William Randall, and Buie by R. A. Williams and E. H. Walker. The present paper is concerned with the laccoliths. Part II on the volcanic rocks, dikes, and stocks will be published at a later date.

For the field work, two base maps were available: the topographic map of the Fort Benton quadrangle by the United States Geological Survey, with a scale of 1:250,000 and a contour interval of 200 feet; and a pace and compass map made by the United States Forest Service with a scale of 2 inches to the mile, showing streams and ridges. The latter map covered only the mountain part of the area included in the National Forest. For the mapping of the dikes a map was compiled from the plats of the county surveyor. Where greater detail was desired, plane-table maps were made of local areas.

The topographic map of the Fort Benton quadrangle was published in 1899 and is of a reconnaissance quality, even for its small scale. The map was enlarged to a mile to the inch to allow space for detail. The geology was put on this map to conform to the topography of the map as well as possible. This involved much generalization and serious difficulties in some areas. However, the map presented is believed to represent, somewhat diagrammatically, the general relations of the rocks and the approximate size and form of the bodies.

The laboratory work was carried on at Harvard University during the winters following the field work.

Utmost thanks are due to the Division of Geological Sciences of Harvard University for a generous grant for financing the work. The writers wish to thank members of the Department of Geology, in particular Professors R. A. Daly and M. P. Billings, for much help and many stimulating discussions. Through the kindness of Professor Adolph Knopf of Yale University several rock specimens collected by Weed and Pirsson were borrowed for study. Mr. F. A. Gonyer made many chemical analyses of rocks and minerals. Finally, the writers wish to express their appreciation to all the residents of the area for their hospitality and helpfulness.

GEOLOGICAL SETTING OF THE HIGHWOOD MOUNTAINS

The Highwood Mountains lie approximately 100 miles east of the Rocky Mountain front (Fig. 1). Seventy miles to the northeast are the Bearpaw Mountains, which are geologically very similar to the Highwood Mountains in that they consist in part of stocks and volcanic masses of alkalic rocks (Weed and Pirsson, 1896a). Fifty miles south-

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east of the Bearpaw Mountains the Little Rocky Mountains rise above the plains. According to Weed and Pirsson, this mountain group is a domical uplift of sedimentary rocks. A quartz porphyry "laccolite" has been injected between the crystalline schists of the basement and

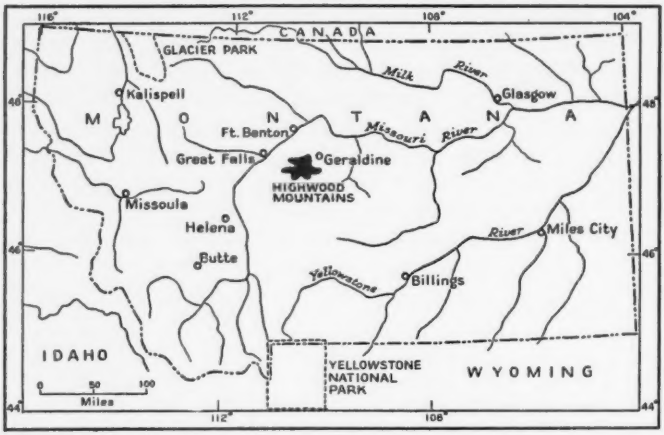


FIGURE 1.—*Location of the Highwood Mountains*

the sedimentary rocks of Cambrian age (Weed and Pirsson, 1896c). The Judith and Moccasin mountains are approximately 60 miles east and a little south of the Highwood Mountains. They are domes which consist of arched sedimentary formations and laccoliths of alkaline rocks (Weed and Pirsson, 1898). The northern end of the Little Belt range lies 20 miles south of the Highwood Mountains; it is a domical uplift modified by minor folds. Intrusions of alkaline rocks of Highwood type occur in the Little Belt mountains (Weed, 1899). These mountain groups, composed in part of alkalic igneous rocks, constitute the petrographic province of central Montana as defined by Pirsson (1905).

To the above-mentioned rocks should be added a group of volcanic and intrusive rocks that lie on both sides of the Missouri River about 50 miles to the west of the Highwood Mountains. Their main mass is west of the town of Cascade at the northern end of the Big Belt Mountains. A reconnaissance study shows them to resemble somewhat the rocks of the Highwood Mountains but to contain more plagioclase. About 100 miles to the northwest of the Highwood Mountains are the syenitic intrusive rocks of the Sweetgrass Hills that also should be included in the same petrographic province.

SQUARE BUTTE, ROUND BUTTE, AND SHONKIN SAG LACCOLITHS

Portion of Shonkin Sag laccolith at left center. Note lower shonkinite, with bench at top formed by weathering of transition rock, and syenite above. Square Butte may be seen above Shonkin Sag laccolith and Round Butte to the right.

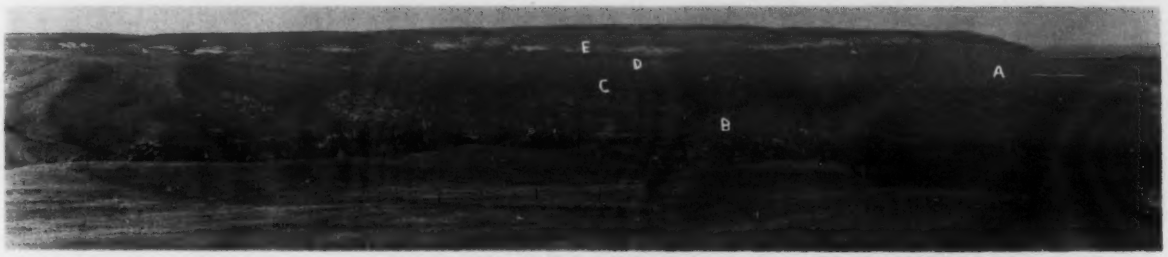


FIGURE 1. WEST OF TANNER'S CANYON
Shows eastern marginal contact of Shonkin Sag laccolith (A) with sills beyond, lower sedimentary contact (B), lower shonkinite (C), transition rock (D), and syenite (E).

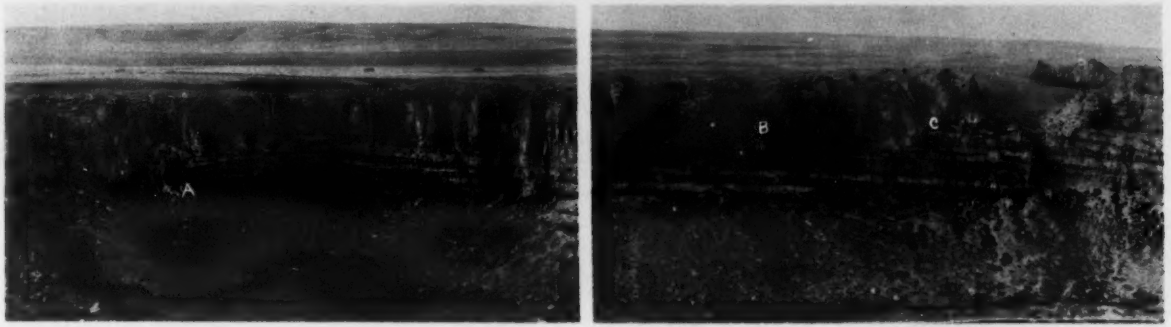


FIGURE 2. PANORAMIC VIEWS
Showing doubly truncated sedimentary abutment on North Cliff of Lost Lake. Dark rock in shonkinite and sills. *See* text for explanation of points A, B, and C.

The igneous rocks of the Highwood Mountains intrude or overlie Cretaceous sedimentary rocks which, according to Reeves (1929), have a regional dip to the northeast of a degree or less. Locally in the mountains the sediments have been faulted and in some places have relatively steep dips. In the plains surrounding the mountains Reeves (1929, p. 166-168) found both thrust faults and normal faults.

Sometime after the deposition of the Cretaceous beds a great area was uplifted and then eroded. In the area of the Highwood Mountains, when this erosion had developed mountains with a relief of several thousand feet, volcanic eruptions took place which filled in the irregularities of the surface and built up a volcanic pile that must have been several thousand feet thick. Both lava flows and fragmental material were spread over the area. Some intrusive bodies must have been formed in the area at this time, but practically none of these has been found. These early volcanic rocks were, insofar as they are still preserved, rather uniform quartz latites.

After these eruptions ceased, erosion was again dominant and continued until the volcanic rocks had been largely removed, and the area was made up of ridges and valleys much like those of the present time and with a relief of several thousand feet.

Renewed volcanism then took place and built up a new mountain mass that must have covered an area somewhat larger than the present mountains and must have been considerably higher. These later volcanic rocks were very different from the earlier ones and look like basalts. They might be called femic leucite, analcime, and pseudoleucite phonolites or jumillites. Nearly all the intrusive rocks of the area belong to this later magmatic cycle and have about the same mineral and chemical compositions as the associated extrusive rocks. They are shonkinites, nepheline syenites, and related rocks. They are chiefly in the form of stocks, dikes, sills, and laccoliths.

Both groups of volcanic rocks are believed to be of Middle Tertiary age, and the duration of the igneous activity was probably very short.

Since the second period of volcanism the volcanic dome has been eroded until only remnants of the old volcanic mountains now remain.

DESCRIPTION OF THE LACCOLITHS

INTRODUCTION

The laccoliths of the Highwood area lie in the relatively flat plains country 3 to 10 miles east and northeast of the mountains of volcanic rock. With one exception they have been intruded into the Eagle sandstone of Upper Cretaceous age, which, according to Reeves (1929, p. 165), has a gentle regional dip to the northeast. The lack of sufficient

horizon markers throughout the region makes it impossible to correlate exactly the relative stratigraphic positions of the laccoliths. Inasmuch as the thickness of the Eagle sandstone is only 250 feet, all the laccoliths

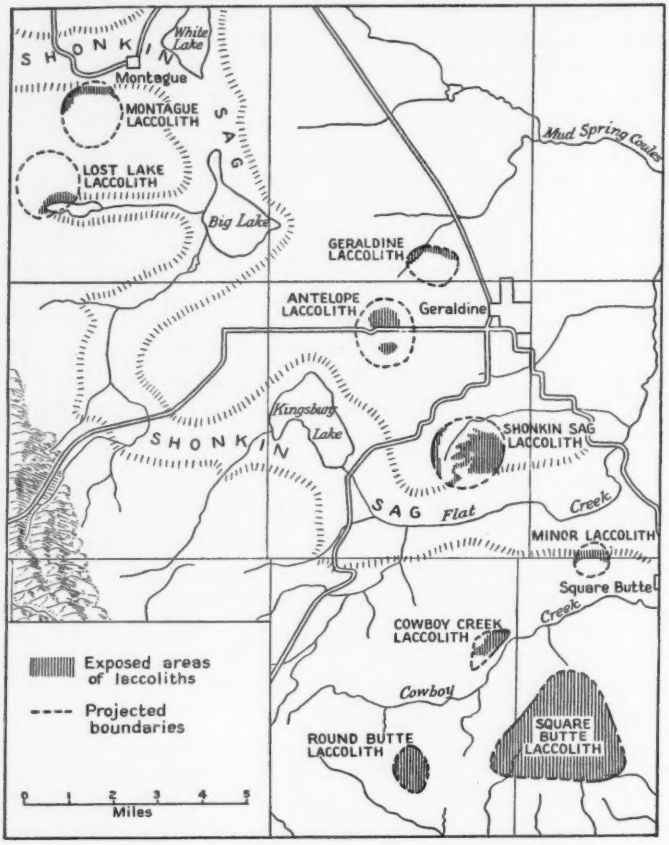


FIGURE 2.—*Index map of the laccoliths of the Highwood area*

must lie very near the same horizon or at most only a little over 200 feet apart.

Nine laccoliths, presenting differing topographic expressions and varying stages of erosion, are visible for study (Fig. 2). Most striking of all is Square Butte; it rises over 2000 feet above the general level of the country and can be seen as a landmark for 75 miles. Round Butte,

formerly known as Palisade Butte, is also a prominent topographic feature and reaches a height of 800 feet above the surrounding plains. Four other laccoliths have their chief exposures as vertical cliffs along Shonkin Sag, the abandoned glacial valley of the Missouri River, or tributaries thereto, and present no prominent rise above the plains. The three remaining are exposed only as remnants dissected by minor streams.

All of the laccoliths are petrographically similar and have shonkinite as their principal rock. Moreover, where erosion has cut deeply enough, a syenite is found overlying the shonkinite. In all of the laccoliths a similar chilled phase of dark rock is in contact with the sedimentary rock and by its constant composition indicates a common source for the intruded magmas.

Because of the many similarities of the various laccoliths, it is unnecessary to give a detailed description of each. Since Shonkin Sag laccolith is of most general interest and most completely exposed, it will be described first, and the others will be compared with it.

SHONKIN SAG LACCOLITH

In spite of the important place occupied by Shonkin Sag laccolith in petrogenetic theory as an illustration of differentiation in place, the only descriptions of it until recently were those of Weed and Pirsson (1895; 1901) and Pirsson (1905), which were based on field work of a reconnaissance nature.

After Weed and Pirsson left the Highwood Mountains in 1896, it was 37 years before additional field work was done there. It seems a remarkable and rather unfortunate coincidence, therefore, that in the summer of 1933 two separate field parties set out independently to again study Shonkin Sag laccolith. The Harvard group spent 6 weeks during June and July of that year studying the relations of the various rock layers to one another and making a detailed topographic and geologic map. Later in the summer, Mr. Julian D. Barksdale of Yale University arrived to survey and study the laccolith in a similar manner. Both parties spent portions of the summers of 1934 and 1935 in further work on the laccolith.

The bulk of the information gathered by the two parties has been duplicated, such as topographic and geologic map, petrographic study, and density determinations. Unfortunate as such a duplication is, it is encouraging to find that two sets of independent observations check so closely. On some important points, however, there is disagreement. Consequently, during the summer of 1938, a short time was spent in the field checking these controversial points. Different interpretations of some observations on Shonkin Sag laccolith and a study of the other

laccoliths in the area have led to conclusions diametrically opposed to those of Barksdale. As a result, the writer feels justified in publishing this account of Shonkin Sag laccolith, which otherwise would be only a repetition of Barksdale's (1937) printed account. However, in order to avoid unnecessary duplication, many of the observations included in the original manuscript have been omitted here. Brief accounts of the geologic relations will be given as a basis for comparison with the other laccoliths in the area.

The greater resistance to erosion of Shonkin Sag laccolith compared to the surrounding sandstone is brought out well in the topographic map, Plate 3. The broad dome formed by the laccolith has been cut into by erosion just sufficiently to give excellent exposures of the intrusive. The vertical cliff facing Shonkin Sag gives a cross section along a chord of the circle outlined by the laccolith, while a tributary has exposed a considerable portion of the upper layers of the igneous rock (Pl. 2, fig. 1).

The nearly circular form of the laccolith as outlined on the geologic map has ample justification from field observations. Two points on the circumference of the laccolith can be seen on the cliff facing Shonkin Sag. The border can also be observed in several small gullies on the eastern flank, while on the ridge at the extreme west it can be traced for several thousand feet. These known portions of the boundary are indicated by solid lines on the map; they lie on a circle, the broken portion of which represents the projected boundary.

As seen from across the Sag, many of the important features of Shonkin Sag laccolith can be observed. Most striking of all is the exposure of the sedimentary floor at the base of the cliff formed of great columnar masses of igneous rock. This floor of sandstone is nearly horizontal and can be seen with only minor interruptions for almost a mile. From the foot of the cliff to the valley floor 400 feet below extends a talus slope strewn with gigantic blocks broken from the igneous columns. At the eastern end of the cliff, sedimentary rock can be seen overlying the intrusive for several hundred yards and dipping to the east at a low angle. It is here that the upper contact can best be studied, for most of the sedimentary cover has been removed from the rest of the laccolith. The upper contact can also be seen for a short distance at the west end of the cliff, but relations are somewhat obscure there owing to overlying gravels.

From a distance one can see that the laccolith is definitely layered with bands of various thickness discernible both by weathering forms and color differences. Indeed, it is only from such a long-range view that one can assign a thickness to the lower and upper chilled phase. Inasmuch as the cliff is vertical for over 100 feet, a detailed study is

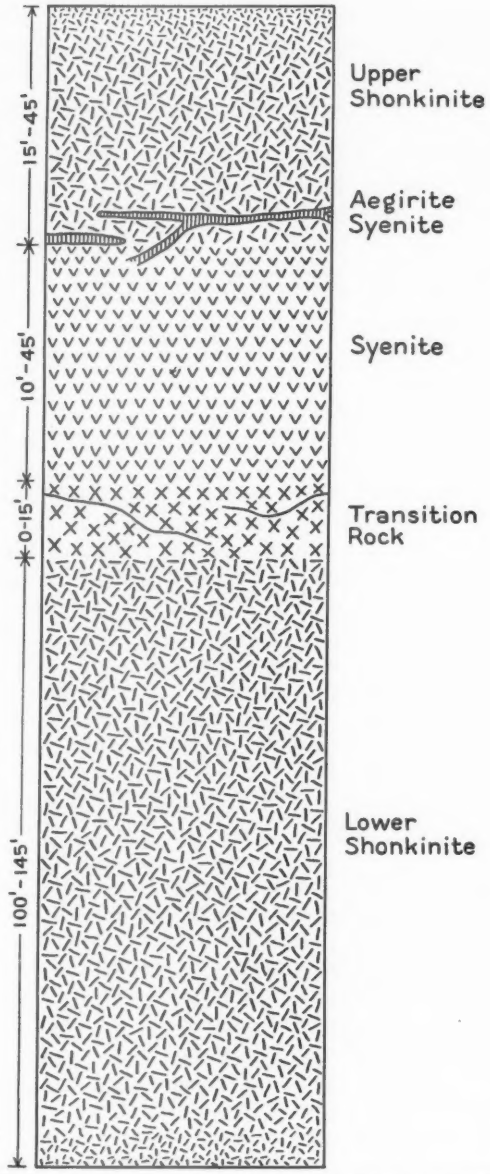


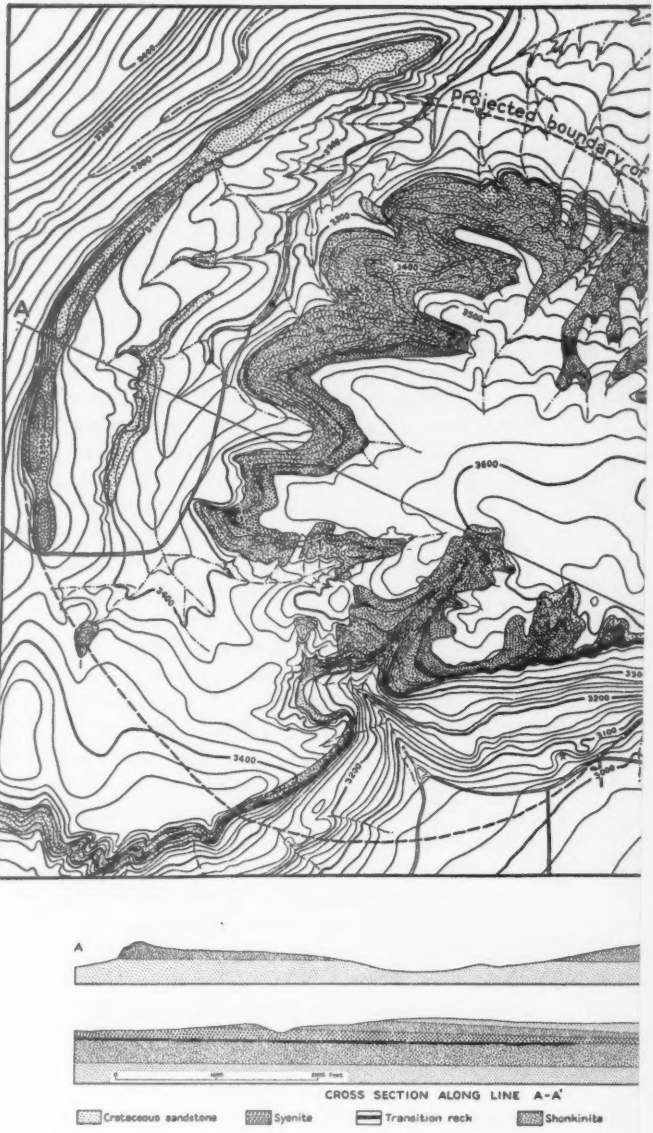
FIGURE 3.—*Generalized section through Shonkin Sag laccolith*

perforce made under difficult circumstances. In two places vertical dikes cut the cliff, and their easy weathering permits one to ascend readily from base to top. Unfortunately, the laccolithic rock is here also weathered and difficult to study. The cross sections in Figure 3 and Plate 3 show the relations of the various layers to one another.

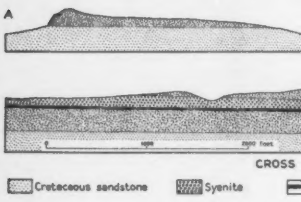
Extending out from the main body of the laccolith are numerous sills, which are best seen at the eastern end of the main cliff, where one can be traced for a mile along the wall of the Sag. Their relations to each other and to the laccolith will be described in detail in a later section. In spite of the fact that the sills merge with the main body of igneous rock, the periphery of the laccolith proper is well defined by definite outward thrusting and arching of the sediments. Thus, at the very margin a thickness of over 100 feet of igneous rock is present.

The sandstone into which the laccolith is intruded is light brown, but at the lower contact a zone varying from a few inches to 3 feet has been altered to a dense, light-blue rock. The alteration at the upper contact is much less pronounced, and a slight baking is the only visible effect. The chilled border phase of the igneous rock has an aphanitic groundmass inclosing phenocrysts of augite and pseudoleucite and was called "pseudoleucite basalt porphyry" by Pirsson (1905, p. 45) and "pseudoleucite-augite vogesite" by Barksdale (1937). Although feldspathoidal qualifications have been used, neither basalt nor vogesite carries with it the implication of a feldspathoidal rock. They have both, therefore, been rejected in favor of "mafic phonolite", which places additional emphasis on the feldspathoidal nature. According to Johannsen's (1931) scheme of classification, a phonolite contains between 5% and 50% dark minerals. The rock under discussion falls very near the upper limit, and some specimens may carry even more than 50% dark minerals. If the rock contained the original leucite, instead of pseudoleucite, it would be a jumillite. The term jumillite is not used partly because of the change of leucite to pseudoleucite and partly because it seems unwise to complicate the nomenclature with an unfamiliar term. The texture of the mafic phonolite at the base of Shonkin Sag laccolith becomes increasingly coarse upward, forming a complete gradation into the coarsely crystalline rock above. It is impossible to select any definite layer where the transition takes place; since the lower dark band appears from a distance to be about 15 feet thick, this figure is taken as the thickness of the chilled phase.

The rock above the mafic phonolite is shonkinite of granitic texture, and dark colored due to the abundance of dark minerals. It is referred to as lower shonkinite in contrast to a higher zone of upper shonkinite. The lower shonkinite ranges in thickness from 100 to 145 feet with



GEOLOGIC MAP AND CROSS SECTION OF SHONK



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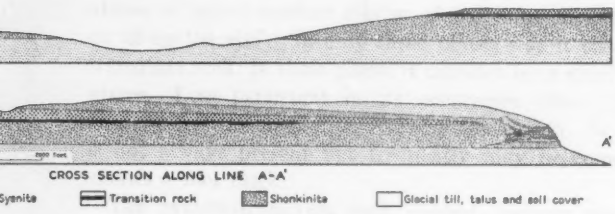


P AND CROSS SECTION OF SHONKIN SAG LACCOLITH

a maximum near the center of the laccolith. It is very uniform in texture but becomes increasingly dark upward. One exception to the uniform change in the lower shonkinite was found in the northern portion of the laccolith. Here, a short distance above the base, is a mass of light-colored shonkinite that grades into the darker, more normal rock surrounding it. At the margin of the laccolith the lower shonkinite presents a finer texture against the inclosing sediments and resembles the mafic phonolite of the base. The thinner sills extending out from the laccolith are composed of mafic phonolite, but toward the centers of the thicker ones the rock becomes coarser and approaches the texture of shonkinite.

From its gross weathering features, the lower shonkinite appears to be a single unit to the base of the transition rock, which is the next definite layer above. However, close examination shows that from 5 to 10 feet below its apparent upper contact it gives way to a much lighter-colored rock of similar texture, called "hybrid syenite-shonkinite" by Barksdale. This rock, in turn, shows in places a complete gradation into the extremely coarse-grained transition rock. Elsewhere the gradation is more abrupt, and a contact can be located within a few inches. The two rocks are so unlike texturally and respond so differently to the agents of weathering that in the average exposure one is led to the erroneous conclusion that a sharp contact exists between them.

Throughout most of its extent the transition rock shows a uniform thickness of about 14 feet; toward the margin of the laccolith it becomes thinner and finally pinches out. It weathers with extreme ease, giving rise to a bench at the top of the shonkinite, and forms vertical or overhanging cliffs capped by the more resistant syenite. For this reason it appears only in a few places on the geologic map.

One of the striking features of the transition rock throughout most of its extent is an irregular dikelet, 3 to 5 inches thick, of a fine-grained, light-colored rock (Pl. 5, fig. 1). At some locations the dikelet is at the top of the transition rock, elsewhere at the middle or bottom. On a cliff this narrow band is found to taper off to a thin stringer, but either above or below another dikelet of the same rock will begin and carry on along the cliff. In only three places was it observed outside of the transition rock; in these places it intrudes for a short distance the syenite above. Less persistent in its occurrence than this leucocratic rock is a dikelet rich in biotite, likewise confined to the transition rock. It is not always present but frequently may be found in wide lens-like masses a foot thick.

The syenite-transition rock contact appears sharp in most places, but in a fresh exposure the two rocks may be seen to grade into each

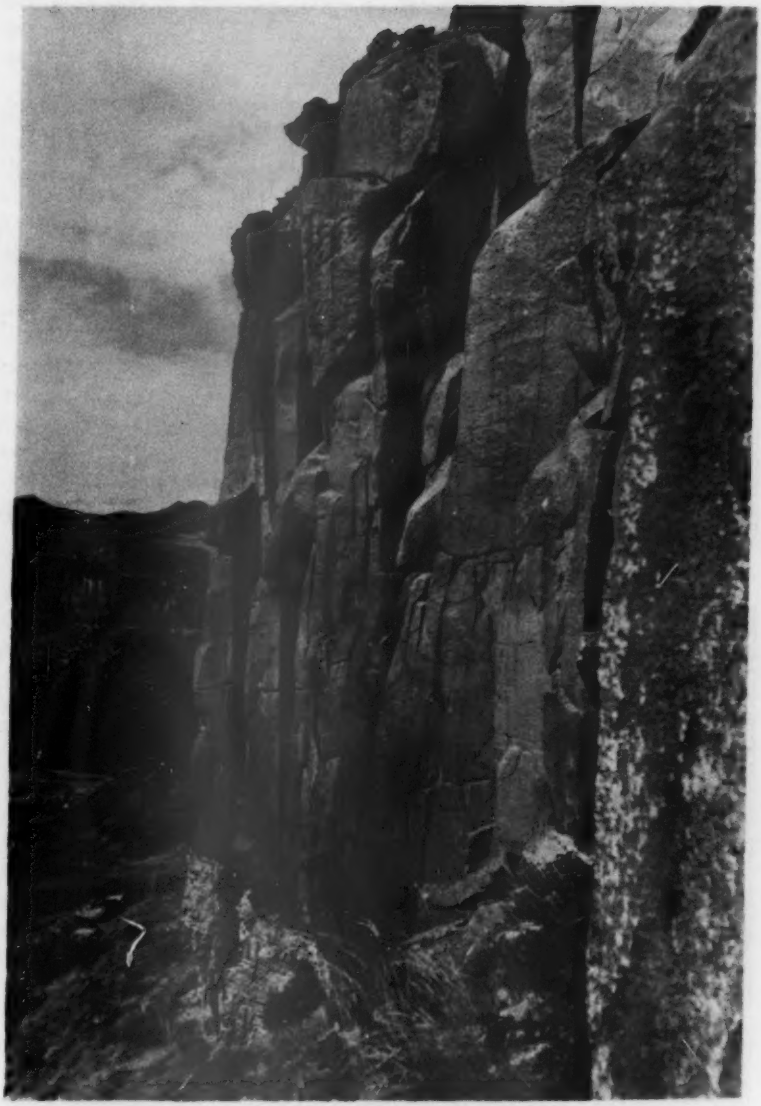
other within a few inches (Pl. 6). The syenite is chalky white on its weathered outcrops but in a fresh exposure is a light-gray rock of granitic texture with dark minerals peppered through a lighter groundmass. Both texture and mineral composition are very uniform throughout the central portion of the syenite, but toward the margins of the laccolith it becomes slightly darker. The syenite is in the form of a lens-like sheet that near the center of the laccolith reaches a maximum thickness of 45 feet and gradually thins toward the periphery.

The upper shonkinite, lighter in color than the lower shonkinite, in most places rests directly on the syenite into which it grades rather abruptly. Pirsson (1905) reported these two rocks separated by a transition rock similar to the one below the syenite. In a few places a coarser rock—the aegirite syenite—does separate the syenite from the shonkinite. More commonly it is found intruding the upper shonkinite in definite sheets one inch to several feet thick (Pl. 7). In places the aegirite syenite is present within and merging with the main syenite. Thus this rock in no way acts as a transition nor is it at all comparable to the transition rock below. The aegirite syenite bears an intrusive relation to the rocks that inclose it; while most frequently it is found in horizontal dikes, it assumes all attitudes and in two places was found extending downward nearly to the base of the lower shonkinite. At the face of the main cliff at its eastern end, the aegirite syenite can be followed to within 60 feet of the margin, where it splits into several small horizontal dikes which in turn grade into narrow stringers of a dense gray phonolite (Fig. 7). The phonolite is commonly found at or near the end of the laccolith intruding the chilled shonkinite.

The upper shonkinite becomes increasingly dark upward and has a thickness that varies from about 15 feet near the margin to 45 feet at the center of the laccolith. It grades vertically upward into a fine-grained phase that lies beneath the sedimentary cover and horizontally into a similar rock at the peripheral contact. This upper mafic phonolite is quite analogous to that at the base of the laccolith, and a thickness of 10 feet is assigned to it. The marginal mafic phonolite is about 20 feet in horizontal extent and continues downward at the outer contact to join the fine-grained phase of the lower shonkinite. There is thus an envelope of chilled rock that completely encloses the other rocks of the laccolith.

SQUARE BUTTE LACCOLITH

Because it is a conspicuous landmark, Square Butte was the first of the laccoliths of the area to receive attention. It was mentioned by the early explorers, but the first account of any if its petrography was a description of the syenite from the top by Lindgren (1893, p. 286). Little



CLIFF OF SHONKIN SAG LACCOLITH

Note massive columnar jointing with sedimentary rocks below. In the background can be seen the western end of the cliff and the Highwood Mountains in the distance.

FIGURE 1. HORNBLENDE-AEGIRITE STRINGER IN TRANSITION ROCK

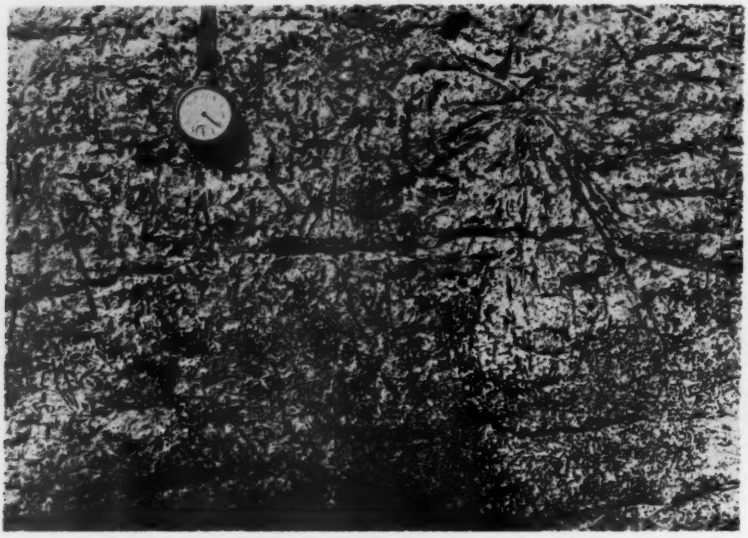


FIGURE 2. TRANSITION ROCK
Showing radiating clusters of long augite crystals.

TRANSITION ROCK OF SHONKIN SAG LACCOLITH

can be added to Pirsson's (1905, p. 49) admirable description of the general appearance and weathering forms of Square Butte, but some important features that escaped his attention will be described.

The igneous mass of Square Butte rests on an elevated platform of Cretaceous rocks that is deeply dissected by streams tributary to Shonkin Sag and Arrow Creek. The name is derived from the fact that the top, though sloping gently to the southwest, is flat and makes almost a right angle with the precipitous upper slopes (Pl. 8, fig. 1). The slopes of Square Butte are in the lower part gentle but become increasingly steep upward, while at the top is a nearly vertical cliff 100 to 300 feet high. A striking feature that can be seen for miles away is a group of narrow crested ridges, called "combs" by the local people, that radiate like dikes from the central mass. In a closer view one sees that these are merely erosional remnants between dissecting gullies. On ascending the butte from the higher land to the west, one finds in vertical section 700 feet of shonkinite overlain by about 700 feet of syenite. From a distance the nearly horizontal contact between these two rock types is clearly seen, as well as a division of the syenite itself that gives the butte a layered appearance.

Unlike Shonkin Sag laccolith, the sedimentary contacts at Square Butte are poorly exposed, for erosion has removed the sandstone from the top, but has not cut deeply enough to expose the base. At three places one can observe the contacts at the margin of the laccolith. On the southeast corner for about 300 feet where the contact is visible, the sedimentary rock dips away from the laccolith at an angle of about 30 degrees. Here a fine-grained rock, somewhat coarser than the mafic phonolite of Shonkin Sag laccolith, grades into the shonkinite that forms the lower portion of Square Butte. The specimen for chemical analysis of the chilled rock was taken from this point. The contact can also be seen at the west and at the east. At these places the sedimentary rock is nearly horizontal to within a few feet of the contact, where it abruptly changes to a nearly vertical position. The marginal phase of igneous rock is here much more resistant than the shonkinite of the interior and stands as a narrow crested ridge. From the top of Square Butte this resistant rock can be seen in the nature of a rampart outlining the laccolith where the actual contact is not exposed. Accepting this ridge as representing the margin, the plan of Square Butte has been outlined from aerial photographs as shown in Figure 2.

A thickness of 700 feet of uniform shonkinite is exposed, but inasmuch as the lower contact is not visible a somewhat greater thickness must be assumed. The "mottled rock" as termed by Pirsson overlies the shonkinite and is so named because clusters of dark minerals sepa-

rated by lighter patches give it a spotted appearance. This rock can be considered the lowest part of the syenite mass, and the contact between it and the shonkinite is relatively sharp but highly irregular with a mutual interfingering of the two. The mottled rock occupies a 150- to 200-foot zone of gradation between the shonkinite and the even-textured syenite that forms the chief rock of the upper portion of the laccolith. From this level on the sides of the more prominent "combs", bare rock surfaces can be seen in continuous exposure to the very top of the laccolith. The uppermost 200 feet of syenite is of a different character from that below and weathers in large rectangular pinkish blocks; this syenite with only minor breaks forms a precipice encircling the entire top of the laccolith.

Although petrographic study shows a change in the character of the syenite from top to bottom, the transitions are, in general, gradational and not in the nature of contacts. However, in the zone 300 to 400 feet below the top, there can be seen on the naked exposures great patches of rock, whiter than the rest of the syenite and separated from it by sharp contacts. These chalky white patches vary from a few feet to 100 feet in diameter and weather more easily than the enclosing rock. In spite of the interrupted nature of this white rock, the close spacing of the patches and their position at a fairly definite horizon gives one the impression, when viewing the butte from a distance, of a definite band completely girdling the laccolith. It forms, in this larger sense, a break that gives the syenite its layered appearance. Even with the complete gradation in vertical section, five horizontal layers of syenite can be discerned on the basis of color. Named in order from the lowest to highest, they are: mottled rock, gray syenite, interrupted white rock, gray syenite, and pink syenite.

The elevated platform on which Square Butte rests extends about half a mile to the north before it is terminated abruptly by the valley of Cowboy Creek, a small tributary to Shonkin Sag. A cliff 150 to 200 feet high rims the high land and rises above the gentler slopes that lead to Cowboy Creek. On this cliff are exposed a score of nearly horizontal sills composed of chilled shonkinite that appear to be the counterpart of the sills extending from Shonkin Sag laccolith. These sills are from 100 to 150 feet below the lowest exposure of the shonkinite of Square Butte, and based on this evidence it seems reasonable to add at least a thickness of 100 feet to the 700 feet of shonkinite exposed.

ROUND BUTTE LACCOLITH

Two miles west of Square Butte on the same elevated ground, Round Butte, so named because of its circular plan and rounded contour, rises

to a height of 800 feet. Streams have not cut close enough to it to remove the material broken from the higher slopes, and as a result Round Butte stands partially buried in its own debris (Pl. 8, fig. 1). Long talus slopes lead up on all but the north side to sheer shonkinite cliffs with a pronounced columnar jointing. These cliffs have been broken through in places, and the talus slopes continue toward the top of the butte. At the north a small valley has cut back into the central part of the igneous mass, giving the top a decided northward slope.

As at Square Butte, the sedimentary cover has been completely removed, and igneous-sedimentary contacts can be found at only three places—at the north, south, and southwest. The northern exposure is 300 to 400 yards from the steep slopes of the side of the butte, and the sandstone is found dipping away from the laccolith at an angle of 40 degrees. The southeast contact is much higher and within a few feet of the shonkinite cliffs. There the attitude of the sedimentary rocks is almost horizontal and indicates that an extremely sharp upturn of the strata was necessary to cover the top of the laccolith several hundred feet above. The south contact shows shonkinite truncating the sedimentary rock.

A cliff of syenite 50 feet high forms on the southeast the highest point of Round Butte (Pl. 8, fig. 1). From its base a talus slope extends downward to the top of the main cliff of columnar shonkinite, thus concealing any contacts that might lie between. Similar conditions exist everywhere at the outer rim of the butte. However, along the walls of the small valley which has been cut into the butte from the north, shonkinite can be traced up into syenite through a transition rock similar to that of Shonkin Sag laccolith but of less constant thickness. On the western side of the valley a thickness of 65 feet was measured, while on the eastern side only 30 feet was to be found. Recalling the ease with which the transition rock weathers at Shonkin Sag laccolith, its presence here undoubtedly accounts for the paucity of exposures below the base of the syenite.

LOST LAKE LACCOLITH

Lost Lake, the most picturesque spot in all the Highwood area, is an alkali lake that lies in a tributary to the Sag, 10 miles northwest of Shonkin Sag laccolith (Pl. 8, fig. 2). It is enclosed on three sides by vertical cliffs of shonkinite, from which numerous sills extend out into the surrounding sandstone. The glacial tributary to the Missouri that carved the valley of Lost Lake, in flowing from west to east, plunged over a resistant laccolithic mass undercutting its base and, in the fashion of Niagara, formed vertical cliffs. At the end of glacial time, the stream had exposed the laccolith for half a mile on the north but for only a few

hundred yards on the southern side. The margin, therefore, must be projected diagonally across the valley in a northeast direction. It seems reasonable to assume that at one time the lower sedimentary contact of Lost Lake laccolith was exposed, although at present it is covered by talus.

Above the steep walls surrounding Lost Lake is a broad bench formed on the north of deeply weathered shonkinite that extends several hundred feet back from the cliff. A quarter of a mile to the north at the top of a low ridge, fine-grained shonkinite can be seen in contact with the overlying sedimentary rocks. It grades downward into coarser rock that 30 feet below the contact is intruded by numerous sills of syenite. From here downward to the rim of the cliff 60 feet below, no exposures are present, nor is there any other outcrop of igneous rock in the area that might conceivably be part of the laccolith. However, Shonkin Sag in swinging around the Highwood Mountains comes within a mile and a half of the head of Lost Lake, and at the top of the valley wall on the southeast side a thick sill of chilled shonkinite is exposed. This sill may well extend back into the main body of the laccolith.

From the southern rim of the valley one can see a most interesting feature displayed on the northern wall. The cliff at the head of the valley is made up of massive shonkinite columns extending to the valley floor. These columns can be followed a hundred yards to the east, where several sills emerge forming the base of the cliff for a mile down the valley. The higher sills have been truncated by a later intrusion of magma, the main body of which overlies the lower sills. This second body terminates in a number of sills that lie over those extending out from the first intrusion. A third intrusion has truncated the sills of the second, as the second truncates those of the first. What might be called, then, the eastern margin of the laccolith is the place where the third and highest intrusion gives way to a series of sills (Point C, Pl. 2, fig. 2).

MINOR LACCOLITH OF SHONKIN SAG

The igneous body called by Pirsson the "Minor laccolith of the Shonkin Sag" lies on the south side of the valley about 3 miles southeast of the "Major" Shonkin Sag laccolith. Above a great talus slope, it presents a cliff 100 to 150 feet high and 1500 feet long of dark massive shonkinite that rises 700 feet above the valley floor. Owing to its greater resistance to erosion than the surrounding sandstone, it projects more than 100 feet from the main valley wall, and may thus be observed on three sides. When viewed from the east or west, the top of the laccolith can be seen to have a dip of 20 degrees to the south, conformable with the overlying sedimentary rocks. At the western side the sedimentary rocks are

sharply folded and, within a few feet, change from a horizontal to nearly vertical attitude in conformity with the steep face of the shonkinite. At the western end of the main cliff the lower sedimentary contact is exposed for a few feet, so that at this point the 100-foot cliff represents the total thickness of the laccolith.

At the center of the main cliff 100 feet above the base is an irregular band of syenite about 20 feet thick that becomes thinner to both east and west and finally ends in thin stringers. The shonkinite-syenite contact is gradational within a few inches. Above the syenite zone shonkinite continues to the top, where it merges with a fine-grained contact phase.

MONTAGUE LACCOLITH

Four miles northeast of Lost Lake, near the village of Montague, a cliff face of Shonkin Sag exposes the Montague laccolith for 1500 feet horizontally and 140 feet vertically. At the top, sedimentary rocks, in contact with fine-grained shonkinite, dip toward the valley at an angle of 30 degrees. From both ends of the laccolith exposed on the cliff, numerous sills break through the sharply folded and thrusted sediments. In the shallow gullies above, intermittent outcrops of shonkinite show a rapid widening to both east and west, indicating that the Sag truncates the laccolith not far from its margin.

About a mile toward Lost Lake from the Montague cliff, shonkinite in contact with sandstone is exposed on the east wall of a small valley. The shonkinite, which appears similar to that found elsewhere, is cut by a few small stringers of a fine-grained syenite. The contact is several hundred feet long and arcuate in plan with the sedimentary rock dipping sharply to the west. A plane-table traverse from the Montague cliff to this exposure showed that the curvature of the contact coincided with the circle determined by it and the two marginal contacts of the cliff. We may assume, therefore, that they belong to the same laccolith, and the three known points on the periphyry determine the diameter to be about 1½ miles.

COWBOY CREEK LACCOLITH

The Cowboy Creek laccolith lies in the upper drainage of Cowboy Creek about 2 miles northwest of the Minor laccolith and just beneath the rim of the high platform that supports both Square Butte and Round Butte. In some places on the east side of the laccolith, the overlying sediments have been removed, and the actual upper igneous contact has been laid bare over a considerable area. The eastern upper contact, where exposed, appears to be of a domal nature. The laccolith has been cut into sufficiently by small streams tributary to Cowboy Creek to enable one to outline fairly well its northern and eastern boundaries, which prove to be

rather irregular. In addition to the irregularity of outline, the Cowboy Creek laccolith is asymmetric and thus differs from most laccoliths of the region. The upper contact on the eastern side dips to the east at about 30 degrees, but to the west the laccolith breaks into a series of horizontal sills as shown diagrammatically in Figure 10.

The greatest thickness of igneous rock exposed in the Cowboy Creek laccolith is about 150 feet, but the total thickness is unknown since the bottom contact cannot be observed at that point. In a gully formed by a small eastward-flowing stream near the northern edge of the laccolith, shonkinite overlies a light syenite that extends to the valley bottom. Thus, here is another example of upper shonkinite above syenite.

OTHER LACCOLITHS

Three miles due west of Geraldine the county road makes an abrupt turn to head a sharp little valley. The precipitous wall of this valley is caused by a resistant rim of mafic phonolite at its top. The mafic phonolite resembles a sill 3 feet thick, but if it is traced to the north it is found to grade upward into the extremely weathered coarse shonkinite of Antelope laccolith. The land rises gently to the east, and intermittent exposures of shonkinite are found as high as 120 feet above the porphyritic phase. At this elevation a coarse syenite forms a horizontal layer about 15 feet thick, remnants of which were found half a mile apart. This syenite resembles in a striking manner the transition rock of Shonkin Sag laccolith; moreover, above it a few feet of finer-grained syenite is present. Seventy-five feet above the syenite more shonkinite is found in isolated outcrops. The evidence, although fragmentary, suggests rather definitely that this was once a laccolith similar in geology and comparable in size to those in the area in a less advanced state of erosion.

On the high land a mile northwest of Geraldine, the base of the Geraldine laccolith is exposed in several places. At the eastern edge of this table land two sills, 10 and 8 feet thick respectively, are present and can be traced out from the main mass of igneous rock. Erosion, however, has removed most of the upper part of the laccolith, and 30 feet of shonkinite in a vertical section is the maximum thickness exposed. The greatest distance between exposures is half a mile, showing that this laccolith was at least somewhat more than half a mile in maximum dimension.

Much of the land northeast of the Highwood Mountains is underlain by shonkinite sills of varying thickness that are not directly traceable to any laccolith. They may be merely sills extending out from hidden laccolithic masses or, which seems more probable, intrusives that lacked sufficient material or force to bow the overlying strata.

PETROGRAPHY

INTRODUCTION

Three or four rock types, as previously pointed out, are common to all of the laccoliths. Petrographic study reveals not only a similarity between corresponding types of the different bodies but also a striking mineralogical likeness between the different rock types themselves. A monotonous repetition of the mineral assemblage exists in all the many thin sections examined, with the differences more quantitative than qualitative. For this reason only the petrography of Shonkin Sag laccolith will be discussed in detail, and the other laccoliths will be compared with it.

SHONKIN SAG LACCOLITH

Shonkinite.—Considerable variation in both composition and texture is shown in the shonkinite of Shonkin Sag laccolith. In all the variations, however, the same minerals are present, and it is only their proportions that differ from place to place. The amount of dark minerals varies from 42 percent by weight at the bottom of the upper shonkinite to 65 percent by weight at the top of the lower shonkinite. As would be expected, the gray color of the rock in the hand specimen becomes increasingly dark with the higher percentages of dark constituents. In general, the shonkinite has a granitic texture but near the sedimentary contacts is finer grained.

Augite, olivine, biotite, apatite, and magnetite in euhedral crystals are imbedded in a matrix composed of potash feldspar, with zeolites and carbonate probably altered from nepheline. The augite crystals are present in all sizes up to 2 centimeters in maximum dimension. Where the larger crystals are abundant, they give a porphyritic appearance to the rock. Osciilatory zoning is common with alternating light and dark bands. A conspicuous feature of some of the augite crystals is a rim of bright-green aegirite-augite, appearing as a marginal reaction and in veins penetrating along cleavage cracks. In some places aegirite-augite is present in tiny crystals scattered uniformly through the rock. For the most part, the augite is fresh with sharp boundaries against the enclosing feldspar, but a slight reaction to produce biotite can occasionally be seen.

Olivine shows its greatest concentration, as does augite, at the top of the lower shonkinite. A brown biotite in aggregates of small flakes forms rims around the olivine separating it from the feldspar. These rims commonly have a green outer portion and are absent where olivine comes in contact with augite or apatite. In some places, large biotite crystals enclose several small olivine grains poikilitically. Few grains are fresh without at least a partial alteration to serpentine along cracks at the

margin, and some have been completely altered. Iddingsite was observed as an alteration product in several specimens but is uncommon.

Biotite, in addition to its occurrence as a reaction product of augite and olivine, forms crystals with sharp outline against the enclosing feldspar. It is strongly pleochroic, varying from a light yellow to a deep brown, and frequently possesses green borders darker than the central part. Apatite, magnetite, and, less frequently, sphene in small, but sharp euhedral crystals are enclosed in all the other minerals.

The matrix of the shonkinite is made up for the most part of a potash feldspar with an axial angle varying from 0° to 10°, and for this reason is called sanidine. Some of the sanidine is altered to zeolites. Nepheline was found only in small amounts in a few thin sections but was probably originally present in considerable quantity and has altered to natrolite and stilbite.

Where shonkinite comes in contact with the sedimentary rock at both the top and bottom of the laccolith, it is a dense mafic phonolite, the "pseudoleucite basalt porphyry" of Pirsson, and the "pseudoleucite-augite vogesite" of Barksdale. A fine-grained matrix encloses phenocrysts of augite, pseudoleucite, olivine, and apatite and is isotropic at the immediate contact, but cryptocrystalline an inch or so away. The texture of the groundmass becomes progressively coarser away from the contact, so that at a distance of one foot small but recognizable crystals of sanidine are found; at 10 to 15 feet the coarse granitic texture of the shonkinite is present. The average mode of the chilled shonkinite at the contact is:

	Per cent		Per cent
Groundmass	56.3	Olivine including alteration products	7.8
Pseudoleucite	19.0	Apatite	1.0
Augite	15.9		

The pseudoleucite at the contact preserves the sharp euhedral outline of the original leucite crystals and is only slightly birefringent. As the rock becomes coarser, the pseudoleucite becomes less abundant and less regular in outline and is made up of fan-shaped aggregates of sanidine and zeolites. At a distance of 15 feet from the contact, pseudoleucite can no longer be recognized as such, but small scattered patches of sanidine and zeolites free from dark minerals indicate its former presence.

The optical properties of the augite show it to be the same as that found in the coarser rock but it is fresher and lacks the aegirite borders. The olivine is considerably altered to serpentine with magnetite separating out along cracks. Biotite rims, brown on the inside and pale green on the outside, surround the olivine. Carbonate is present, altering from both the groundmass and pseudoleucite. Zeolites, so abundant in

the coarser shonkinite, are here present only sparingly in the pseudoleucite in combination with sanidine. There appear to be two generations of both the dark minerals and pseudoleucite, for, in addition to the large phenocrysts several millimeters across, crystals of microscopic size are scattered through the matrix, and few of intermediate sizes are present.

The contact of mafic phonolite and the blue baked sandstone below is sharp even in thin section, and little evidence of metamorphism is shown. Medium-sized quartz and feldspar grains are present in the sandstone with irregular masses of carbonate enclosed in a brown isotropic matrix.

Rock densities.—During the course of field work, density determinations were made to check those on which Osborne and Roberts' theory of differentiation was based and to get a rough quantitative measurement of the obvious differences existing in the shonkinite. Over 150 such determinations were made on specimens collected at 10- to 15-foot intervals from 10 nearly vertical sections through the laccolith. The range in density was from 2.58 to 3.01. Figure 4, modified from Barksdale (1937, Fig. 8, p. 341), shows the distribution of rock densities at several sections through the laccolith as determined by him, together with the densities determined during the present work.

These two sets of independently derived data in general agree very well and show an increasing density upward through the lower shonkinite. The greatest differences appear in sections I and II, which were taken on the cliff face where the presence of two eroded dikes make ascent possible. The rock adjacent to these eroded dikes is itself badly weathered, and it is extremely difficult to get fresh material for density determinations. This fact no doubt accounts for the lack of agreement. Since Barksdale's density determinations in section II were so at variance with those determined by the writer and since this is an important section because it goes from floor to roof of the laccolith, another complete section was taken during the summer of 1938. Although it was in places a most difficult task, great care was taken to get fresh rock. These specimens yielded the densities shown in Figure 4, section II. It will be noted that they are in good agreement with the earlier determinations. A redetermination of the densities of section I did not seem advisable, since even with a sledge hammer it was impossible to get fresh material.

At only three places in Shonkin Sag laccolith can complete sections be taken from top to bottom, owing to the erosion of the upper shonkinite. Table 1 shows the densities and percentage of heavy minerals of specimens collected from section II of Figure 4; Figure 5 shows graphically this distribution. Section II is selected for this, for here the horizontal displacement from top to bottom is less than 150 feet.

Although upward increase in density of the shonkinite may at first be thought of as unusual, it is not peculiar to Shonkin Sag laccolith. Determinations made on the shonkinite of Round Butte and Lost Lake laccoliths showed a similar increase in density from the bottom upward. Mr.

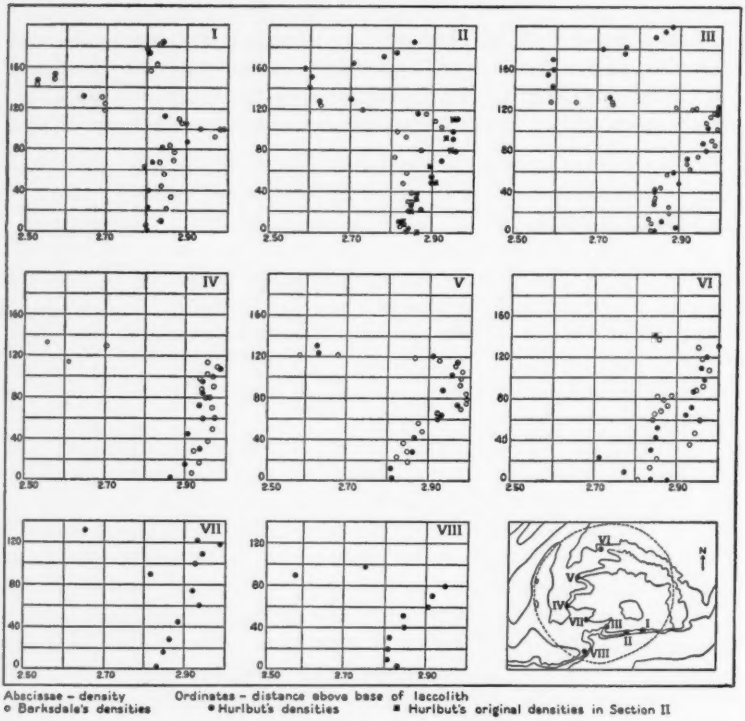


FIGURE 4.—*Rock densities in Shonkin Sag laccolith*

This figure is modified from Barksdale (1937, Fig. 8, p. 341)

William Pecora reports a like density distribution at Box Elder laccolith in the Bear Paw Mountains. Density determinations made on a drill core from Rattlesnake Butte laccolith showed an extremely uniform increase in density upward from the floor. Further study might show that this is common to many of the thin differentiated igneous bodies.

Syenite.—The name syenite was given to this rock by Pirsson and to avoid the introduction of any other term is retained in the present discussion. However, it is somewhat misleading, for the rock has the chem-

ical composition of a nepheline syenite rather than a normal syenite, although the original nepheline has been almost completely altered.

The main syenite, unlike the shonkinite, is a very uniform rock both in texture and mineral composition. The amount of heavy minerals varies

TABLE 1.—*Rock densities and percentage of heavy minerals in Section II of Shonkin Sag laccolith*

	Feet above base	Density*	Weight % of heavy minerals
	185	2.85	
Upper Shonkinite	175	2.82	46.1
	170	2.78	44.2
	165	2.72	42.0
Syenite	160	2.59	19.3
	150	2.60	18.1
Transition Rock	135	2.62	28.7
	125	2.63	32.4
	110	2.95	65.0
	95	2.93	64.6
	80	2.94	63.6
Lower Shonkinite	65	2.89	58.4
	50	2.91	56.5
	35	2.86	51.4
	20	2.86	51.2
	10	2.84	49.2
	0	2.86	

* Density and heavy-mineral determinations were made on specimens collected in 1935, shown by ⊗ in section II, Figure 4.

from 18 per cent to 25 per cent by weight. The resulting high percentage of light constituents gives the rock a white chalky appearance in the outcrop. The syenite is a medium-grained rock, similar in texture to most of the shonkinite, but the color difference is sufficient to distinguish them readily.

The same minerals found in the shonkinite are present in the syenite, but in different proportions. Augite, biotite, olivine, apatite, and magnetite as euhedral crystals are again found in a matrix composed mostly of sanidine. The optical properties of the augite show it to be nearly identical in composition to that found in the shonkinite, but a greater percentage of the crystals are rimmed with aegirite-augite. Biotite is present both as euhedral crystals and as rims around augite and olivine. It is brown to light yellow and has, in most cases, later and much darker biotite growing on it in parallel position. The initial crystals were tabular, flattened parallel to (001), while the added material has grown

as slender spines or needles normal to that direction. Olivine is rare in the syenite and is found either enclosed within augite or surrounded by a reaction rim of biotite. Apatite, magnetite, and sphene are found scattered through the rock associated with both light and dark minerals.

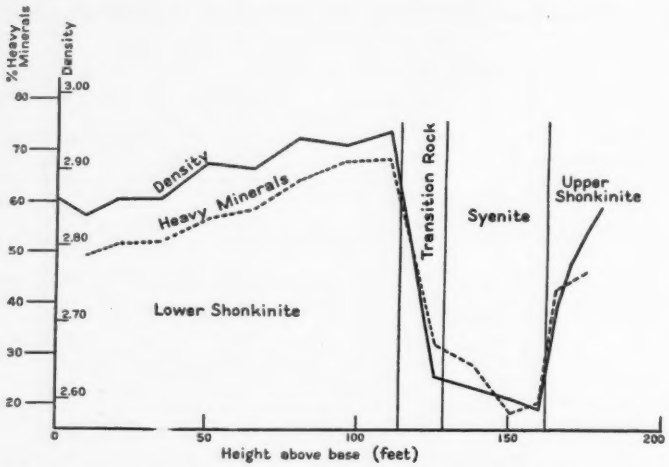


FIGURE 5.—*Variation of rock densities and heavy mineral percentages with height in Shonkin Sag laccolith*

The matrix of the above-mentioned minerals is largely sanidine and zeolites. Occasional grains of albite and microcline are present, but their total quantity is so small as to be negligible. The sanidine is less altered than in the shonkinite and is frequently found as large subhedral grains poikilitically enclosing earlier minerals.

Although some variations are to be found in the mineral composition, the following mode may be considered typical of the fresh syenite:

	Per cent		Per cent
Sanidine	40	Magnetite	2.0
Zeolites	32	Apatite	0.5
Augite and aegirite	15	Olivine	1.0
Biotite	6	Others	3.5

Transition rock.—The transition rock separates the main syenite from the lower shonkinite; although its qualitative mineralogical composition is similar to theirs, it is vastly different texturally. The grain is so coarse that a microscopic description loses much of its ordinary significance, and even a hand specimen is too small to show the true relations of all the

minerals. (See Plate 6.) The most striking feature seen when viewing a cliff of this rock is the numerous star-shaped clusters formed by long augite crystals radiating from common centers. These crystals vary in length from place to place, but frequently are found 6 inches long. The largest cluster observed had a diameter of 17 inches, and the individual prisms of augite measured over 8 inches in length. At the center of these clusters is a nucleus composed of a graphic intergrowth of augite and sanidine. In places, this intergrowth may follow out the long augite crystals for several inches from the center. There seems to be no rule for growth of this kind, for in a given cluster only one or all of the crystals may be incased in it. The graphic intergrowths are found not only as nuclei of the augite clusters but also as isolated aggregates packed closely together. They are more resistant to weathering than the enclosing minerals and frequently may be picked from a cliff in masses resembling English walnuts.

Biotite is conspicuous in the hand specimen, and blades of it, elongated parallel to the axis of symmetry, are frequently found paralleling the augite crystals and in part altering from them. In addition, equidimensional flakes an inch or more in diameter are scattered through the rock. The sanidine in the hand specimen is much less conspicuous than augite and biotite, but interrupted cleavage surfaces an inch across can be seen.

The more detailed relations of the minerals of the transition rock can be seen under the microscope. Much of the augite is surrounded by green aegirite-augite. Brown biotite is altering from augite both as narrow rims and as larger irregular patches. The augite of the graphic intergrowths is relatively free from alteration to either aegirite or biotite, although the sanidine with which it is associated is considerably zeolitized. Euhedral crystals of biotite surrounded by darker borders of the same mineral are present. Olivine is an uncommon mineral but is found in occasional grains surrounded by augite. Apatite, magnetite, and sphene are here found in slightly larger crystals than elsewhere in the laccolith.

Sanidine is the principal mineral of the groundmass of the transition rock, but orthoclase (a potash feldspar with large axial angle), nepheline, and sodalite are also present in small amounts. All four of these minerals have been much altered to zeolites—chiefly natrolite, stilbite, and chabasite. Large patches are found where the primary minerals have completely gone over to zeolites. This alteration undoubtedly accounts for the extreme ease with which the transition rock weathers.

The aplitic dikelet so persistent within the transition rock is composed of about 90% sanidine somewhat altered to zeolites and 10% aegirite

and hornblende with only a few scattered grains of biotite, augite, and apatite. A complete description of this body is given by Barksdale (1937, p. 348-349). The dark irregular segregation in the transition rock is rich in biotite both as tabular euhedral crystals and as rims altering from augite. The typical sanidine and accessory mineral combination of the other rocks is here present, and, except for the absence of olivine, this rock resembles a shonkinite. The mode is:

	Per cent		Per cent
Feldspar and zeolites....	54.8	Magnetite.....	2.7
Biotite.....	21.0	Sphene and apatite.....	0.6
Augite.....	20.9		

Aegirite syenite.—The aegirite syenite, the "upper transition rock" described by Pirsson, is intruded in thin sills into the upper shonkinite. In the hand specimen this rock characteristically shows feldspar crystals an inch or more across poikilitically enclosing long prisms of augite and blades of biotite. Microscopically it is found that all the pyroxene grains are in part or completely altered to aegirite. Furthermore, second-generation aegirite occurs in bundles of radiating fibers associated with zeolites. The biotite blades, so conspicuous in the hand specimen, are a light brown with dark irregular borders and are elongated parallel to the *b* crystallographic axis. As in the other laccolith rocks, sanidine altered to zeolites is present, but much of the zeolitic material is probably an alteration of nepheline. Abundant tiny apatite and magnetite crystals are present.

Phonolite.—The dark-gray aphanitic rock found intruding shonkinite at the margin of the laccolith, and believed to be an offshoot of the aegirite syenite, is termed phonolite (Barksdale's microsyenite). The familiar array of minerals is present: augite and aegirite, biotite, sanidine, and zeolites. In the hand specimen, as well as under the microscope, occasional large crystals or aggregates of augite, olivine, and sanidine are found that bear the same relation to one another as in the shonkinite. It appears that the phonolite has separated crystals from the older but not completely solidified shonkinite. Such crystals are found as xenocrysts in the phonolite.

Chemistry.—In Table 2 are listed all the available chemical analyses of the rocks of Shonkin Sag laccolith with the norms calculated from them. These include five new analyses by Gonyer, which now gives an analysis for each of the rock types found. Some of the older analyses are not so significant as they would be if the locations from which the rocks came were more definite. Thus, analysis 3 by Roberts was made

CONTACT ZONE OF SYENITE AND TRANSITION ROCK, SHONKIN SAG LACCOLITH

The syenite is above, transition rock below. Note graphic intergrowths of augite and sanidine near bottom of picture.

FIGURE 1. AEGIRITE SYENITE
In small stringers in upper shonkinite.

FIGURE 2. COARSE BANDS OF AEGIRITE SYENITE
Aegirite syenite light colored, shonkinite dark colored.

AEGIRITE SYENITE IN UPPER SHONKINITE

TABLE 2.—*Chemical analyses and norms of rocks of Shonkin Sag laccolith*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	46.06	47.76	45.77	47.88	48.78	49.88	47.92	50.72	53.72
TiO_2	1.07	0.76	0.76	0.77	0.90	0.42	0.76	0.79	0.21
Al_2O_3	11.05	13.28	8.94	12.10	17.20	16.17	13.62	18.60	19.58
Fe_2O_3	3.04	2.35	3.63	3.53	4.09	3.77	3.44	3.52	3.30
FeO	5.82	5.78	7.13	4.80	4.29	3.42	4.79	3.24	2.46
MnO	0.30	0.12	0.13	0.15	0.06	0.42	0.11	0.09	0.14
MgO	8.03	8.62	12.96	8.64	4.18	3.26	7.44	2.14	1.14
CaO	10.02	10.10	11.56	9.35	5.36	5.00	8.70	4.26	2.50
Na_2O	2.50	1.58	1.40	2.94	4.25	4.28	2.68	4.33	5.63
K_2O	6.25	6.53	4.60	5.61	6.95	7.84	6.20	7.87	9.24
H_2O-	0.16	....	0.18	0.70	....	0.67	....	....	....
H_2O+	2.04	2.16	0.95	1.52	3.28	2.64	2.66	3.43	1.78
CO_2	1.39	0.14	....	0.12	0.20	0.35	....	....	....
P_2O_5	1.21	0.08	1.52	1.11	0.15	1.33	0.83	0.15	....
Cl	....	....	....	tr	....	....	....	....	....
BaO	0.52	0.22	0.26	0.46	0.47	0.60	0.53	0.70	0.15
SrO	0.08	0.08	tr	0.13	....	....	0.16	0.10	0.04
S	....	0.19	....	....	0.06	....	0.08	0.04	....
	99.54	99.75	99.79	99.81	100.22	100.05	99.92	99.98	99.89
				NORMS					
or	18.90	11.67	17.24	32.53	41.14	46.15	28.36	46.70	54.49
ab	....	....	....	....	....	6.29	....	3.14	4.19
lc	13.95	20.93	7.85	0.66	....	....	6.54	....	....
ne	11.36	7.38	6.53	13.35	19.60	16.19	12.50	17.89	23.29
an	0.56	9.73	4.17	3.34	7.23	1.95	6.39	8.06	1.11
di	33.39	32.93	34.56	28.44	16.31	17.54	27.67	12.91	9.26
wo	....	....	....	....	....	....	....	....	0.35
ol	7.90	9.34	17.83	9.08	4.96	3.76	7.37	0.69	....
il	2.13	1.52	1.52	1.52	1.67	0.76	1.52	1.52	0.45
mg	4.41	3.25	5.34	5.10	6.03	5.57	4.87	5.10	4.64
ap	2.69	....	3.70	2.69	0.33	2.79	1.86	0.31	....
cc	....	0.30	....	....	....	....	....	....	....

(1) Pseudoleucite basalt porphyry (mafic phonolite). E. S. Roberts, analyst. Osborne and Roberts (1931).
(2) Mafic phonolite just west of Tanner's canyon. F. A. Gonyer, analyst.
(3) Lower shonkinite. E. J. Roberts, analyst. Osborne and Roberts (1931).
(4) Middle lower shonkinite. W. F. Hillebrand, analyst. Weed and Pirsson (1901) and Pirsson (1905).
(5) Transition rock from talus block. F. A. Gonyer, analyst.
(6) Syenite. E. J. Roberts, analyst. Osborne and Roberts (1931).
(7) Upper shonkinite 10 feet above syenite. F. A. Gonyer, analyst.
(8) Aegirite syenite at top of main cliff. F. A. Gonyer, analyst.
(9) Phonolite from eastern end of main cliff. F. A. Gonyer, analyst.

on shonkinite which was assumed to be from the bottom of the lower shonkinite. It has a density of 3.00, and Barksdale, comparing it with specimens of known location, concluded that it came from the top of the lower shonkinite—an assumption that seems most reasonable.

Analysis 5 was made on material collected from a block of fresh transition rock found in the talus. Twenty specimens were taken from an area of about 25 square feet and were ground together. The analysis was then made on a sample of the resulting composite. Even such a sample

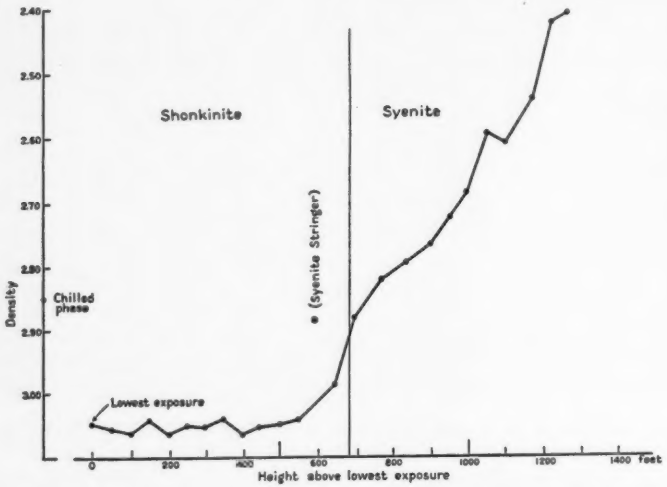


FIGURE 6.—*Variation of rock densities with height in Square Butte laccolith*

may not be truly representative of the transition rock because of its extreme coarseness.

SQUARE BUTTE LACCOLITH

Shonkinite.—Shonkinite as a rock type was first described from Square Butte. It is here very uniform in color and mineral composition and throughout its thickness of 700 feet has a uniform specific gravity and approximately 70% of heavy minerals by weight (Fig. 6). Except for the much higher percentage of dark components, the mineral assemblage is the same as described in the shonkinite of Shonkin Sag laccolith. The characteristic mode is:

	Per cent		Per cent
Augite	50	Sanidine, nepheline, and zeolites altered from them	30
Biotite	13		
Olivine	5	Apatite, magnetite, sphene.	2

The relative amounts of the various mafic minerals varies somewhat, but the total percentage of dark minerals remains almost constant throughout the shonkinite. The optical properties of all the minerals

show them to be nearly identical to those in the shonkinite of Shonkin Sag laccolith. The augite, however, is less zoned and lacks the green borders of aegirite but does have biotite as a reaction product. Olivine is surrounded by biotite, but iddingsite and serpentine are frequently found. In addition to being found as a reaction product, biotite is euhedral in some places.

The border phase of the shonkinite at Square Butte, as exposed on the south side, is a fine-grained rock with abundant crystals of augite. Microscopically, sharp well-formed augite crystals are imbedded in a matrix of finely crystalline feldspar and augite. There is no fresh olivine, but numerous pseudomorphs of serpentine after olivine are present; considerable carbonate is also present as an alteration of the feldspathic groundmass. Resorbed masses of pseudoleucite are found with the outline of the original leucite partially preserved. Apatite and magnetite in tiny grains are scattered through the groundmass.

Syenite.—Above the shonkinite of Square Butte, the mottled rock forms the lowest member of the series of syenites. Its mineralogy is qualitatively similar to that of the shonkinite but with sanidine and zeolites predominating over the dark minerals. Clusters of biotite flakes half an inch to an inch in diameter enclose crystals of olivine and augite. These clusters separated by larger areas of sanidine give the rock its mottled appearance. Augite is the same as that of the shonkinite, but the olivine has a mean index of refraction of 1.760—much higher than olivine of the shonkinite.

Olivine, which is a common mineral in the mottled rock, is found less and less abundantly upward and 250 feet below the top it is nearly absent. In a similar manner, augite gradually decreases in amount upward, owing in part to a more complete alteration to biotite. About 250 feet below the top of Square Butte, hornblende makes its appearance as a reaction product of augite. From here upward biotite decreases in amount, giving way to more and more hornblende both as alteration from augite and as euhedral crystals. Approximately 100 feet below the top, biotite and augite are entirely absent, and a brown unaltered hornblende is the only dark mineral. It is this hornblende-sodalite syenite from the top of Square Butte that Lindgren (1893) so well described and that Pirsson (1905) assumed, quite erroneously, to make up all of the light-colored rock.

The change in the felsic minerals in the 700-foot syenite zone is much less pronounced than that of the mafic. Sanidine with zeolites, chiefly natrolite and stilbite, are the light minerals of the mottled rock as they are in the shonkinite below. However, a few grains of albite,

microcline, and unaltered nepheline are present in the mottled rock and become somewhat more abundant toward the top of the laccolith. In addition to the zeolites mentioned, hydronephelite and chabazite are important alteration products.

About 200 feet below the top, sodalite and nepheline are found in small amounts occupying the interstices between tabular sanidine crystals. The sodalite increases in amount upward and at the top makes up as much as 10% of the rock. The rock from the top of Square Butte contains a small amount of analcime altering from the nepheline and feldspar. Lindgren reported 16% of albite in this rock, but in several thin sections examined the maximum amount found was about 10%. The percentage of albite is difficult to determine, for it is intimately intergrown with sanidine. This sodalite syenite is the only laccolithic rock in which albite is found in appreciable amounts. In many places, the sodalite and nepheline are leached out, giving the rock a highly porous texture.

Chemistry.—The three available chemical analyses of the rocks from Square Butte are given with their norms in Table 3. Analysis A is of the shonkinite made by Pirsson (1905); analysis B is new and was made by Gonyer of the chilled rock from the south side of the laccolith. Inspection of the two analyses shows that, compared to the chilled phase, the shonkinite has become enriched in iron, magnesium, and calcium oxides and impoverished in silica and alumina. Analysis C by Melville is of the sodalite syenite from the top of Square Butte. It differs from all the other analyses of the Highwood rocks because of the unusual mineral content of the rock. Sodalite, albite, and hornblende are here found abundantly and are nearly absent in all the other rocks.

All of these minerals are comparatively fresh, but some alteration to zeolites and cancrinite is shown. An unaltered brown hornblende with green borders and showing constant optical properties wherever it is found is the only dark mineral. The accessory minerals magnetite, apatite, and sphene, abundant in most of the syenite, are present here in only small amounts. In many places in this sodalite syenite there are patches of coarse rock surrounding miarolitic cavities. Fine crystals of sanidine, hornblende, and zeolites are found projecting into the open spaces.

The white chalky rock that forms the interrupted band around the central part of the syenite is found microscopically to be not very different from the rock surrounding it. It is composed dominantly of sanidine, nepheline, and sodalite with a small amount of augite altering to hornblende and biotite. Its mineral composition is similar to that of

the sodalite syenite 200 feet above. The gray rock enclosing this white syenite has a mineral composition quite in accord with its location in the vertical section. It lacks the hornblende and sodalite of the white rock and, in addition, has small amounts of olivine.

TABLE 3.—*Chemical analyses and norms of rocks from Square Butte*

	(A)	(B)	(C)
SiO_2	46.73	48.74	56.45
TiO_2	0.78	0.82	0.29
Al_2O_3	10.05	14.32	20.08
Fe_2O_3	3.53	4.30	1.31
FeO	8.20	4.51	4.39
MnO	0.28	0.11	0.09
MgO	9.27	6.24	0.63
CaO	13.22	8.68	2.14
Na_2O	1.81	1.89	5.61
K_2O	3.76	5.80	7.13
H_2O	1.24	3.01	1.77
P_2O_5	1.51	0.81	0.13
S	....	0.08	....
BaO	....	0.34	....
SrO	....	0.14	....
Cl	0.18	....	0.43
	100.56	99.79	100.45
Norms			
or	22.24	34.47	42.26
ab	1.05	6.29	28.30
an	8.06	13.06	9.73
ne	7.95	5.39	3.41
di	38.19	21.43	....
ol	11.54	6.40	5.91
mt	5.10	6.26	1.86
il	1.67	1.52	0.61
ap	3.70	1.86	0.34
so	....	....	5.96
co	....	....	0.20

(A) Shonkinite from Square Butte. Analyst, L. V. Pirsson (1905, p. 97).
(B) Chilled rock, south side of Square Butte. Analyst, F. A. Gonyer.
(C) Sodalite syenite from top of Square Butte. Analyst, W. H. Melville (W. Lindgren, 1893, p. 296).

ROUND BUTTE LACCOLITH

The contact phase of the shonkinite of Round Butte in the two places where it is exposed is made up of augite, pseudoleucite, and olivine phenocrysts set in a fine-grained feldspathic matrix. On the southwest side of the laccolith, it can be observed grading into coarse shonkinite. Except for the higher percentage of olivine throughout and for the nearly

complete alteration of feldspar to zeolites, this rock is similar to the shonkinite of Shonkin Sag laccolith. Although the transition rock of these two laccoliths is similar in mineral composition, that from Round Butte is much the less uniform. A rock composed almost wholly of coarse tabular sanidine crystals may form a lens-like mass surrounded by rock richer in dark minerals, or the texture may be found to change rapidly over a short distance while the composition remains constant. The syenite of Round Butte differs from that of Shonkin Sag laccolith in the almost complete absence of olivine and in the somewhat less altered sanidine.

LOST LAKE LACCOLITH

As the geologic relations of the Lost Lake and Shonkin Sag laccoliths are very similar, so also is the petrography. The many sills at Lost Lake are composed of porphyritic shonkinite coarser at the centers than the margins. The lowest exposures in the black shonkinite cliffs have a quantitative mineral composition similar to rock 20 feet above the base of Shonkin Sag laccolith, and on this evidence it may be inferred that the base of the laccolith is not far below. Mineral separations show a regular increase of the heavy constituents from the bottom upward with 68% by weight at the top of the cliff. Both the chief mineral components and the alteration products of this rock are similar to those of the shonkinite of Shonkin Sag laccolith. Olivine is invariably surrounded by biotite rims, and aegirite borders of augite are common, while the feldspathic material from both bodies shows the same amount of zeolitization.

On the low hill a quarter of a mile back from the north rim of Lost Lake, the mafic phonolite exposed in contact with sediments grades down into shonkinite. The lower part of this shonkinite is cut by numerous sills and stringers of syenite ranging from a few inches to 3 feet thick; petrographically they are almost identical with the aegirite syenite of the Shonkin Sag laccolith. The large sanidine crystals, bladed biotite, euhedral crystals of aegirite and augite, as well as the secondary radiating fibers of aegirite associated with zeolites, are all present. With so many features in common between these two laccoliths, it does not seem unreasonable to assume that there is present at Lost Lake, between the top of the cliff and the shonkinite-syenite exposure 60 feet above, a zone of transition rock overlain by syenite. Indeed, it may be the presence of just such a zone that accounts for the very definite bench at the top of the cliffs.

MINOR LACCOLITH OF SHONKIN SAG

In both the chilled and granular shonkinite, as well as in the syenite of the "Minor laccolith," the same array of minerals is found that exists

in the laccoliths already described. The amount of heavy minerals in the shonkinite varies in vertical section with the greatest percentage just below the syenite and the least just above, quite analogous to Shonkin Sag laccolith.

MONTAGUE LACCOLITH

One of the best illustrations of unaltered mafic phonolite was found in a sill extending out from the main mass of the Montague laccolith. Euhedral phenocrysts of pseudoleucite, augite, and serpentinized olivine are surrounded by an isotropic matrix in which not even the beginning of crystallization is visible. The mode of this rock is as follows:

	Per cent		Per cent
Augite	17.1	Groundmass	51.2
Pseudoleucite	21.0	Apatite	0.5
Olivine	9.9	Magnetite	0.3

Similar porphyry but with the groundmass somewhat coarser is present at the top of the laccolith.

The 140-foot thickness of shonkinite exposed in the Montague cliff shows only minor differences in the percentage of heavy minerals and, with the exception of Square Butte, is more uniform in its quantitative mineral composition than any similar thickness of shonkinite elsewhere. Here again, the similarity to the shonkinite of Shonkin Sag laccolith is striking, with the only noticeable difference a wider border of reddish-brown biotite surrounding the olivine.

COWBOY CREEK LACCOLITH

The chilled rock at the Cowboy Creek laccolith is similar to that at Shonkin Sag laccolith, but the phenocrysts are smaller. The shonkinite is likewise finer grained with augite, biotite, and olivine poikilitically enclosed in feldspar. No nepheline is present, but in thin section considerable interstitial zeolites are to be found. The syenite shows an unusually small amount of alteration, and most of the rock is made up of large crystals of sanidine enclosing dark minerals.

At one place near the northeastern boundary of the Cowboy Creek laccolith, numerous inclusions are to be found. They are all similar petrographically and are made up of fine granular pyroxene enclosed in feldspar. In some of the inclusions, biotite flakes and small masses of carbonate are present.

ANTELOPE LACCOLITH

The Antelope laccolith west of Geraldine shows a lower shonkinite similar to that of the Shonkin Sag laccolith. The overlying syenite however, is a coarse variety with bladed biotite, long augite crystals, and

graphic intergrowths of feldspar and augite. This rock corresponds to the transition rock of the Shonkin Sag laccolith in all respects except that its texture is finer; moreover, it occupies a similar position with respect to the shonkinite. The chilled border phase of the shonkinite differs slightly from that found elsewhere, for biotite in large flakes is found here as phenocrysts considerably resorbed and altered to magnetite and chlorite. The biotite phenocrysts are absent from the coarse shonkinite, and their reaction must have been more complete.

PETROGENESIS

INTRODUCTION

Of the nine laccoliths described herein, five have adequate exposures to give a cross section from top to bottom. Four of these are horizontally layered with a thick layer of shonkinite at the base, overlain by syenite, and a thin layer of shonkinite at the top. Three other laccoliths have syenite over shonkinite, but the upper contacts have been removed by erosion. This same relation of light and dark rock is found in both Box Elder Butte and in Rattlesnake Butte laccoliths near the Bear Paw Mountains, northeast of the Highwood Mountains. Moreover, many concordant igneous bodies have been described from various parts of the world with a layering of light over dark rock. An excellent summary of 54 of these bodies is given by Daly (1933, p. 334). The repetition of the layering in these thin sills and laccoliths suggests that the layering is not due to the mere chance of outside forces, but that a common internal process has been operative. Therefore, any theory advanced to account for the rock types of one of the Highwood laccoliths must be applicable to all of them. Since, as previously stated, Shonkin Sag laccolith has focused attention on the Highwood area, the discussion of petrogenesis will be centered about it, and the slight differences in mechanism necessary to account for certain features of the other laccoliths will be pointed out.

PROPOSED HEORIES

Several theories have been advanced to explain the layering in the rocks in the Shonkin Sag laccolith. The first, by Pirsson (1905, p. 187), has been well summarized by both Osborne and Roberts (1931) and Barksdale (1937), and only a brief statement of it need be given here. This theory of differentiation in place called for crystallization and convection giving rise to a complete shonkinite shell. The femic minerals would crystallize and attach themselves to the cooler upper and outer surfaces, leaving a salic residue to form the syenite in the interior. Osborne and Roberts pointed out unsound reasoning in Pirsson's hypoth-

esis of differentiation, while Barksdale showed that it did not fit the newly observed field evidence.

After a laboratory study of Pirsson's material, Osborne and Roberts (1931, p. 346-348) advanced the following more plausible theory. Specific gravity determinations indicated a decrease in density downward through the upper shonkinite and an increase in density downward through the lower shonkinite. Crystal settling was offered as an explanation of the observed density distribution. The early-formed phenocrysts of femic minerals settled slowly to the bottom, and owing to increasing viscosity the separation was not complete, but successive layers formed upward with less of the heavy minerals. At the top contact the femic minerals also tended to sink, but settling was so slow that the crystals were overtaken by the advancing solid layer.

"As the rate of solidification became slower, however, augite crystals escaped being entrapped and slowly sank to the bottom. Thus the advancing solid layer contained less and less augite, and the lower part of the upper shonkinite was formed."

The syenite is considered to be the result of the crystallization of the liquid portion after most of the augite had settled, while the coarse augite of the transition rock is pictured not as forming in place but rather while settling through the "central liquid ahead of the downforming syenite."

The density determinations made during the present study (Fig. 3) show that the rock of greatest density is always at the top of the lower shonkinite and not at the bottom. The exact reversal of Osborne and Roberts' density distribution in the lower shonkinite is no doubt due to the fact that their specimen (No. 5676), which was merely assumed to be from the bottom of the lower shonkinite, was actually from the top. The decrease in gravity downward through the upper shonkinite was corroborated by the present study.

Reynolds (1935) advanced the theory of assimilation of a sandstone layer to form the syenite. This idea was based on a faulty diagram of Pirsson's (1905, p. 54) in which he showed the sandstone terminating at the margin of the laccolith rather than arching over it (*Cf.* Fig. 7). Since neither the field relations nor petrographic study support this idea, no further mention will be made of it.

Unable to accept any of the above theories, Barksdale (1937, p. 354-358) has advanced the idea of three separate injections to account for the layering in Shonkin Sag laccolith. The first intrusion is postulated as being of shonkinitic magma forming a laccolith approximately 165 feet thick in the central portion. To account for the density distribution in the lower shonkinite it is suggested that the magma became more mafic as intrusion progressed.

"The second injection, syenite, took place before the shonkinitic laccolith had completely solidified."

The syenite magma advanced up the re-opened conduit and moved upward until it encountered the crystalline shonkinite 40 to 50 feet below the top. There it spread laterally to form the main syenite layer. The magma mixed with the shonkinitic magma below to form a hybrid at the contact, and to some extent mixed with the overlying nearly crystalline shonkinite. At this same time small dikes of syenite were injected into the overlying shonkinite and out to the periphery of the laccolith where the smaller ones were chilled forming a "microsyenite."

Barksdale further postulates that the shonkinite had become solid before consolidation reached the base of the syenite and that during the time between the consolidation of these two rocks a zone of weakness existed at the base of the syenite. It is believed that during this interval a pegmatitic magma, as the third intrusion, made way for itself along the zone of weakness. Pegmatitic material found in the syenite is given as proof of the intrusive relation that exists between the two rocks. The injection of the "narrow dikelet" of hornblende-aegirite syenite is given as the final stage in the formation of the laccolith.

It has already been noted (Fig. 4) that many of the specific gravity determinations made by Barksdale do not agree with those made during this study. Since the density distribution throughout the whole laccolith is highly important in a discussion of petrogenesis, a remeasurement of the specific gravity of all the specimens in the laboratory was made. They were found to be in accord, within the limits of error, with the field determinations of Figure 4. One fact that must be explained is the increasing density upward through the lower shonkinite. Another equally significant fact is the increasing density upward through the upper shonkinite. This density distribution was observed by Osborne and Roberts (1931, p. 348) but ignored by Barksdale. In fact, if Barksdale's hypothesis of an increasingly femic shonkinite magma is correct, the upper shonkinite should have its greatest density at the bottom and least density at the top—the exact reversal of the observed facts. Moreover, on Barksdale's assumptions, the top of the lower shonkinite and the bottom of the upper shonkinite should be of the same density, since it is postulated that they were adjacent to one another. Density determinations show shonkinite from these two places to be the most dissimilar.

In the other laccoliths of the Highwood area, where syenite is present, the thicker the total mass of igneous rock, the greater is the percentage of syenite. Thus, in the Minor laccolith with a total thickness of 150 feet, only about 20 feet is syenite; while in Square Butte with a total thickness of about 1600 feet at least 700 feet is syenite. It would appear that the larger the body, the more complete the differentiation. Where the relations can be observed, the other laccoliths show a succession of

rocks similar to that found in Shonkin Sag laccolith with syenite between a thin upper layer and thick lower layer of shonkinite. It seems extremely improbable that in each case the conduit should have been reopened to admit the syenite magma at the correct time during the consolidation of the shonkinite, and that much syenite was injected in those bodies where much shonkinite already existed, and little syenite where little shonkinite existed.

PREFERRED THEORY

Although many of the observations made during the present study are quite in accord with Barksdale's, the interpretation of them is at considerable variance. Barksdale arrived at a theory of separate injection, while similar observations convinced the writer that a theory of differentiation in place is in better accord with the observed facts. In commenting on an early report of the present work, Barksdale (1937, p. 352) states,

> "Accepting the hypothesis of differentiation in place from a single intrusion, Hurlbut has recently suggested, as proof of the hypothesis, . . ."

Since this statement may be taken to imply that effort was directed to find evidence supporting differentiation in place, it should be pointed out that after the first season's field work the theory of separate injections seemed best to explain the observed field facts. A brief statement of this idea was published by Larsen *et al.* (1935). This hypothesis was clung to until further field and laboratory work forced its abandonment in favor of a theory of differentiation in place.

In an effort to get a more accurate determination of the variations that exist in a vertical section through the laccolith, heavy-mineral separations were made on the specimens of section II, Figure 4. The results are given in Table 1. The heavy-mineral separations were made rather than Rosiwal determinations to avoid the errors made by the latter method in coarse-grained rocks. A calculation of heavy minerals in a columnar section through the laccolith was made using the values given. By weighting the various percentages according to the proportion of the column represented by each, the average percentage of heavy minerals in a column through the laccolith was found to be 49.0. This compares closely with the figure of 49.2 per cent of heavy minerals in the lowest shonkinite that was coarse enough to permit separation. Analysis 2 (Table 2) of the chilled shonkinite was made on a rock taken not far from the base of the section under consideration. The norm calculated from this analysis gives 48.8 per cent of heavy minerals. The remarkably close agreement of these three percentages is possibly fortuitous but, nevertheless, lends considerable strength to the argument of differentiation in place.

It will be recalled that the mafic phonolite forming the envelope around the laccolith is composed of a dense matrix enclosing well-formed crystals of pseudoleucite, augite, and olivine. Inasmuch as it is agreed with Daly (1932, p. 342) that this rock represents a quenched sample of the intruded magma, these phenocrysts must have existed at the time of injection. Osborne and Roberts (1931, p. 343) suggest that the large leucites formed in the upper part of a deeper magma reservoir, and that, therefore, most of them were in the earliest mass of shonkinite intruded. However, since a sill of typical mafic phonolite can be traced back into and found merging with the shonkinite of the laccolith 30 feet above the base, it must be assumed that the chilled phase in all its details is representative of the intruded magma. It is the thesis here presented that under the influence of gravity the sinking of heavy minerals accompanied by minor floating of leucite gave rise to the rock types of Shonkin Sag laccolith.

The sinking of heavy crystals as a method of differentiation is now generally accepted as a result of Bowen's work. The rising of crystals is less commonly considered to be an active factor in differentiation, for only rarely do crystals form that are lighter than the liquid from which they crystallize. However, the rising of crystals is not without support from the literature. The floating of sodalite (Ussing, 1911, p. 352), nepheline (Fersman, 1929, p. 175), leucite (Neubauer, 1911, p. 199; Loewinson-Lessing, 1899, p. 155), and tridymite (Bowen, 1915, p. 176) have been described either from artificial melts or from field evidence. In a horizontal pipe-like body (to be described later by Buie), evidence indicates that leucite has risen in a shonkinitic magma to form a concentration at the top. The fact that leucite may have risen in Shonkin Sag laccolith cannot be ignored in a discussion of the differentiation of that body.

So many unknown quantities are involved that it is difficult to be quantitative regarding the relative importance of sinking of heavy minerals and rising of leucite. The mafic phonolite has a density of about 2.85 and is made up of a groundmass containing about equal amounts of light and dark constituents. If the magma, of which it represents the chilled phase, were 10 per cent lighter, its density would have been about 2.57 before any crystallization began. This figure approximates the density of the liquid phase at the time of intrusion, since up to that time leucite and dark minerals had crystallized in about equal amounts. Pseudoleucite made up of orthoclase and nepheline would have a density of approximately 2.57 or slightly lower. Under such conditions, its tendency to rise would be negligible. If reaction or unmixing to form pseudoleucite had not taken place at the time of intrusion and if leucite with a

density of 2.49 was involved, the tendency to rise would have been greater. According to Larsen and Buie (1938), the present phenocrysts of pseudoleucite may have originally been either leucite rich in soda or analcime rich in potash. If analcime, density 2.29, were involved, there would have been a definite tendency for the crystals to float. There is no positive evidence as to the nature of the phenocrysts at the time of intrusion; consequently, they will be mentioned as leucite.

Augite and olivine with densities of about 3.20 would have had a considerable density differential with the magma and would thus have settled. It is assumed in the following discussion that crystal settling was the most important cause of differentiation, but rising of leucite played a minor role.

Let us consider what took place in the upper part of the laccolith after the magma containing about equal amounts of phenocrysts of leucite and heavy minerals was intruded. A process similar to that described by Osborne and Roberts (1931, p. 351) took place. The chilled phase formed at the immediate upper sedimentary contact, below which crystal fractionation was operative. However, the rise in viscosity, owing to cooling from the upper contact, prevented much movement and rendered the rock just below essentially the composition of the original magma. More heavy minerals would be able to settle out, and more leucite could rise into each successively lower layer before downward increasing viscosity prevented movement. A layer was finally reached in which a nearly complete separation of the heavy minerals had taken place. From here downward, the fluid portion of the magma was the essential component, plus a small amount of floated leucite. This break in mineral composition is the contact of upper shonkinite with syenite below; it parallels the upper sedimentary contact since it was controlled by cooling from that surface.

If the rise of leucite were quantitatively important, a considerable concentration should have taken place in the syenite zone, and the bottom of this zone of concentration now forms the bottom of the syenite. The composition of the rock should be, then, that of the residual liquid plus a certain amount of leucite. In regard to the feldspathic constituents, it is difficult to be quantitative because of the alteration of these constituents. At present there is only one analysis of the pseudoleucite in the Highwood area—that given by Larsen and Buie (1938). This analysis, with minor constituents omitted, is given here. With it are shown the same constituents found in the analysis of the transition rock. This rock, according to the theory here outlined, is the crystallized residual liquid. Therefore, the correct percentage of pseudoleucite plus the correct percentage of interstitial liquid should be equivalent to the syenite.

If it is assumed that there was 50% pseudoleucite and 50% interstitial liquid, the composition should be as indicated in column C, Table 4. Assuming 20% pseudoleucite and 80% interstitial liquid, the composition of the syenite should be as shown in column D, Table 4.

TABLE 4.—*Calculated composition of the syenite*

	(A) Pseudo-leucite	(B) Intersti-tial liq.	(C) 50% A 50% B	(D) 20% A 80% B	(E) Syenite
SiO_2	56.9	48.8	52.9	51.0	49.9
Al_2O_3	22.6	17.2	19.9	18.3	16.2
Na_2O	3.9	4.3	4.1	4.2	4.3
K_2O	10.8	7.0	8.9	7.8	7.8

As will be seen from a comparison of C and D with E of Table 4, the calculated composition of the syenite D is in much better agreement with the analysis of the rock than is C. On this chemical evidence, therefore, we cannot assume a high concentration of leucite in the syenite zone, but a minor accumulation may well have taken place.

While the heavy minerals were settling out of the upper part of the laccolith, they were concentrating in the lower portion. Cooling near the basal sedimentary contact produced a chilled rock, and, owing to lack of time for any appreciable crystal fractionation to take place, the rock immediately above has essentially the composition of the original magma. However, the same forces as were operative at the top of the laccolith caused some leucite to rise and augite and olivine to sink. Thus, rising viscosity, due to cooling from the lower contact, found each successively higher layer more enriched in heavy minerals. The top of this zone was most enriched in femic minerals for it retained much of the olivine and augite from the overlying magma.

As a high concentration of heavy minerals, approaching a close packing, was reached at the top of this zone, settling of heavy minerals in the whole layer was slow owing to the retarding influence of the viscous flow of liquid around the crystals. Any mafic crystals forming above would settle relatively quickly to the top of this zone forming a marked break between it and the mother liquor above. Rising viscosity prevented a complete separation of dark minerals, and above the top of this layer was a zone a few feet thick somewhat enriched in dark minerals; this formed a gradation into the mother liquor. Barksdale accounts for this gradational zone by the mixing of a shonkinite and syenite magma.

When cooling prevented further crystal separation, there was a zone at the top of the laccolith 45 to 50 feet thick that contained progressively less dark minerals downward (upper shonkinite). At the same time, a zone 110 to 145 feet thick had formed at the bottom of the laccolith

that was progressively richer in dark minerals upward (lower shonkinite). Between the bottom of the upper layer and the top of the lower layer was a zone 60 to 70 feet thick composed essentially of the fluid portion of the magma with some additional leucite in the upper part and some additional mafic minerals in the lower part. Cooling and crystallization of this upper part gave rise to the syenite.

Crystallization of the rock at both the top and bottom of the laccolith brought about a concentration of the volatiles in the still liquid portion of the center. The layer of residual liquid is pictured as forming a few feet above the zone of lower shonkinite and below the zone of any leucite concentration. This magma, enriched in volatiles and well insulated from the cooler outer contacts, crystallized slowly and formed the coarse transition rock.

The few feet of rock separating the lower shonkinite from the transition rock is residual liquid plus a small amount of dark minerals that, cooling from the lower contact, crystallized to form the gradational syenitic rock.

Because of the sheet-like nature of Shonkin Sag laccolith, it is assumed that cooling from the upper and lower contacts took place at approximately the same rate. The transition rock which represents the locus of the final liquid phase is nearer the top than the bottom of the laccolith. An explanation for this is found in the distribution of the liquid and crystalline phases of the differentiated magma. The lower shonkinite is made up of the fluid portion of the intruded magma plus a considerable percentage of femic minerals and minus a small amount of leucite. Some of the femic minerals that settled were intratelluric; others crystallized after the magma was intruded. These last dark minerals to crystallize gave up latent heat of crystallization to the surrounding fluid in the upper part of the laccolith, and were extracted from the system. All of the sinking crystals displaced upward an amount of liquid equal to their volume. When final crystallization of the lower shonkinite took place, much of the material was in the solid phase, and crystallization progressed rapidly. At the upper part of the laccolith, however, only a small part was in the solid phase, and crystallization of the considerable fluid portion with the resultant release of latent heat retarded crystallization. Thus, we find the zone of transition rock nearer the top than the bottom of the laccolith.

Little importance can be attached to analyses 3 and 4 of Table 2 because of the uncertainty of the locations from which they came. However, the norm of analysis 7, made on upper shonkinite taken from 10 feet above the syenite contact, shows a lower percentage of dark minerals than the two lower shonkinite norms. Moreover, as would be expected

from the above-outlined theory, this norm shows a lower percentage of dark minerals than the norms of the chilled rock.

Analyses 5 and 6 of Table 2, of the transition rock and syenite respectively, are very similar. They agree as well as most analyses that have been made on rocks from the same body but collected from different locations. The most striking difference is in the amount of K_2O; the syenite shows nearly 1 per cent more of this oxide than does the transition rock. The additional potash in the syenite is accounted for by leucite that floated into that layer.

The small sill-like body found in the transition rock is aplitic in appearance and bears the same relation to the transition rock that aplites commonly bear to pegmatites. It is not one continuous sheet but is made up of many intrusions of varying attitude at different horizons within the transition rock. This aplitic sill, then, can be thought of as an example of auto-injection originating as a differentiate of the residual magma.

After differentiation was nearly complete, there was a final injection of shonkinite similar in composition to the originally intruded magma. Evidence of this later intrusion is the light shonkinite at the north of the laccolith. It was this later intrusion that produced the outward thrusting of the margin. Field evidence shows that the thrusting took place at about this time, for the fault can be traced well back into the crystalline shonkinite.

This late injection of shonkinite took place after partial crystallization of the syenite and caused some of the interstitial mother liquor to be intruded into the overlying shonkinite forming dikes and stringers of the aegirite syenite. Similar material forced outward into the cooler shonkinite at the margins of the laccolith crystallized more rapidly to form the phonolite. The auto-injection of the phonolite took place during the marginal thrusting and was intruded along slickensided surfaces. The late increase in the volume of the laccolith also caused slight movement of the various differentiated layers over one another. Such movement would tend to destroy the minor irregularities existing between them, giving rise in places to sharp contacts. At the same time, the movement might locally cause a mutual interfingering.

DIFFERENTIATION IN THE OTHER HIGHWOOD LACCOLITHS

The relation of the various rock types to one another in the Lost Lake, Round Butte, Montague, Cowboy Creek, and Antelope laccoliths, as well as the mineralogical make-up of each type, indicates a process of differentiation similar to that described for Shonkin Sag laccolith. Round Butte and Antelope laccolith show an increasing percentage of dark min-

erals upward through the main shonkinite, while the syenite and transition rock correspond in position to these rocks in Shonkin Sag laccolith. At Lost Lake laccolith an increase in density upward through the shonkinite is found; transition rock and main syenite are not found but are reasonably inferred. At Montague the uniform percentage of dark minerals in a vertical section is believed due to the fact that the only cliff that permits adequate sampling is very near the margin of the laccolith, where cooling prevented crystal fractionation. The "Minor" laccolith of the Shonkin Sag, owing to its lesser thickness, cooled before complete crystal separation took place; although the mafic minerals increase upward to the syenite, no transition rock was formed.

At Square Butte, the relations are different from those in any of the other laccoliths. Density determinations at regular intervals through the shonkinite showed the rock to have a uniformly high density. The density varied from 3.04 to 3.07, and the percentage of heavy minerals from 69 to 72 by weight. The 700 feet of syenite, as previously described, changes appreciably in mineral composition in a vertical section and toward the top has a progressively lower density (Fig. 6). It is, thus, a composite body that is more in accord with the accepted method of differentiation by fractional crystallization than the other laccoliths of the area. The differentiation that gave rise to these conditions is believed to have taken place in the following manner:

The known thickness of Square Butte laccolith is 1400 feet, but, inasmuch as the upper and lower contacts are not exposed, its actual thickness was at a minimum 200 feet greater. The cooling of a mass of magma 1600 feet thick must have been extremely slow compared with a thickness of 250 feet at Shonkin Sag laccolith. The base of the laccolith is not visible, but we may assume that cooling from the lower contact produced a rock that upward became progressively richer in dark minerals. A level, near the base, may be pictured that became saturated, so to speak, with the close-packed settling crystals before increasing viscosity prevented movement. From here upward, the slow cooling of the thick body permitted the maximum amount of augite and olivine to settle, thus giving rise to the uniform shonkinite of high density. In this manner an almost complete separation of the dark minerals into the lower zone of the laccolith was effected.

This method of obtaining the shonkinite of Square Butte can be checked in a rough quantitative manner. Assuming that there was 100 feet of upper shonkinite above the syenite, the heavy minerals that settled out of it would just about equal those that settled into the bottom 100 feet at the base of the laccolith. Therefore, 700 feet of the upper laccolithic mass (the syenite) contributed to the 700 feet below enough heavy min-

erals to raise their percentage from 40 (as shown in the norm of the chilled phase) to 70 in the shonkinite. The mode of the chilled phase shows about 30% of mafic phenocrysts. Therefore, the complete transfer of mafic phenocrysts from the syenite to the shonkinite would be just sufficient to give the net result of 70 per cent. The transfer of heavy minerals, however, was not complete, as evidenced by their high percentage in the lower layers of the syenite. These may be pictured not as original phenocrysts but as crystals that formed after emplacement and settled out of the upper syenite.

A comparison of the chemical analyses and norms (Tables 2 and 3) of the chilled shonkinite of Square Butte and Shonkin Sag laccolith shows the former to be somewhat more salic. In spite of this fact, the Square Butte rock shows the higher percentage of mafic phenocrysts and a lower percentage of pseudoleucite. At Square Butte, therefore, we must assume a more advanced state in the crystallization of the magma, resulting in a greater density difference between the fluid portion and the dark minerals at the time of intrusion and a lesser differential between the magma and the leucite. The rise of the leucite would here be negligible. Above the shonkinite, then, there was a thick zone with the composition of the intruded magma minus the mafic phenocrysts and plus an equal amount of upward-displaced liquid.

Because of its flat surface the present top of Square Butte is believed to approximate the bottom of an upper shonkinite. Wherever shonkinite and syenite are in contact, the syenite is much less susceptible to weathering; consequently it seems reasonable to assume that erosion has removed the upper shonkinite but has not cut deeply into the syenite.

The slow rate of cooling in such a thick mass would permit near the top almost complete removal of the heavy minerals. Not only the original femic phenocrysts would have ample time to settle, but also many of the dark minerals that formed after intrusion. Moreover, volatiles and heat liberated by the crystallization of early minerals would make this zone more fluid and thus aid gravity. If time were not sufficient to allow a complete separation, one would expect to find more and more dark minerals in each successively lower layer. These conditions would account for the sodalite syenite of the top, where a small percentage of hornblende is the only dark mineral. The increased amount of volatiles at the top gave rise to hornblende instead of augite and explains the presence of chlorine to form the sodalite. Volatiles were less abundant 200 feet below the top, where augite is found partially altered to hornblende and where sodalite is rare. The progressive increase of femic minerals downward evidenced at first by more augite, and in the lower layers by olivine, shows that crystal settling had not been com-

plete. The refractive index of the olivine in the syenite is higher than that in the shonkinite, indicating crystallization after emplacement of the magma and the settling of the earlier-formed olivine crystals.

STRUCTURE AND MECHANISM OF INTRUSION

INTRODUCTION

The laccoliths of the Highwood Mountain region are structurally outstanding in two respects: (1) Most of them are broad, sill-like bodies—not high domes as in the Henry Mountains; (2) the peripheral contacts are not simple magma wedges as shown in textbook illustrations but involve multiple sill injection, thrust and normal faulting in addition to minor bending of the sedimentary rocks.

Because of the vertical cliffs produced when the Missouri River flowed through Shonkin Sag and undercut the laccoliths, several end contacts are well exposed. Detailed study of these provides evidence bearing on the mechanism of growth of the laccoliths. It is possible to establish a chronology which is of importance in connection with petrogenetic theories concerning the rocks of the laccoliths.

An intrusive relation between two rock types is so commonly used as a proof that the intrusive is later and is a separate injection of that rock type from an external source that it is the tendency of any one seeking to prove separate injection to seek merely such an intrusive relation. The prevalence of local intrusion of syenite into shonkinite in Shonkin Sag laccolith led to the early conclusion of the Harvard party (Larsen *et al.*, 1935) that the rock types were emplaced by discrete injections; the same reasoning led Barksdale to the same conclusion. It is of utmost importance to recognize clearly that a later surge of the parent magma may cause movement in the differentiating magma of the laccolith, producing local injection of the more fluid component into the less fluid. The next step is to establish criteria by which this "auto-injection" can be distinguished from intrusion of a different magma from an external source. Detailed study of the syenite-shonkinite relations in the laccoliths supplies many indications that the local intrusion in these bodies is due to auto-injection.

SHONKIN SAG LACCOLITH

General considerations.—The periphery of Shonkin Sag laccolith is more completely exposed than that of any other laccolith in the region. In addition, the cliff where the eastern edge of the laccolith is cut by Shonkin Sag provides the best single exposure of any contact. As shown in Plate 9 and Figure 7, the sedimentary cover, floor, and wall are well exposed. A great deal of information can be gained by the study of this

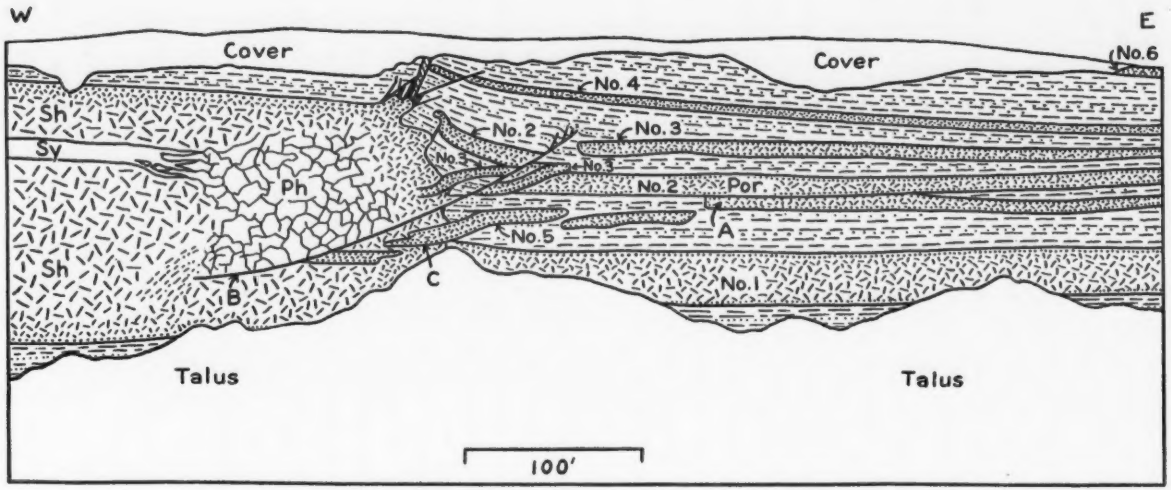


FIGURE 7.—*Eastern end contact of Shonkin Sag laccolith*

This contact, shown in Plate 9, is corrected for fore-shortening and details have been added from cliff study. Lines in shonkinite proportional to grain size shows chilling of laccolith and sills. Syenite (Sy) to left of termination is diagrammatic. Ph is diagrammatic representation of phonolite stringers in brecciated shonkinite.

exposure from the valley floor. This has been supplemented by detailed study of the face of the cliff. Such a study is arduous, but with the aid of a rope sling all critical points may be reached with safety providing normal care is taken to avoid falling stones.

Nature of laccolith boundary.—This exposure shows the typical peripheral structure of the Highwood laccoliths. Instead of simply bending up over the laccolith end, the sediments just east of the contact were lifted partly by the forcible injection of the fringing sills, partly by the thrust fault, and partly by upward bending. There is an additional displacement at the contact along a steep normal fault at the end of sill No. 4. The sedimentary displacement due to sill injection, thrusting, and bending may be accurately measured on the cliff, and the throw on the normal fault is then taken as the difference between this total displacement and the thickness of the laccolith at the contact. The displacements are as follows:

	Feet
(1) Displacement due to sill injection	
Sill No. 1 (Barksdale incorrectly gives 55 feet)	34
Sill No. 2	8
Sill No. 3	6½
Sill No. 4	3
Sill No. 5	7
Total	58½
(2) Displacement due to bending and thrusting (Sill No. 4 used as datum)	57
(3) Since the measured thickness of the laccolith at this point is 135½ feet, the displacement on the normal peripheral fault may be calculated as 135½−(58½+57) = 20 feet, but it seems reasonable to subtract from this the thickness of sill No. 6 (10 feet) because that sill is not traced over the laccolith. Probable displacement on fault	10

This last displacement is calculated on the assumption that there is no assimilation of sediments by the magma of the laccolith. The sandstone is so thinly bedded and lenticular that it was impossible to trace the bedding and so prove directly that there had been no assimilation. However, the sharp nature of the contact, the lack of any considerable alteration of the sediments, and the paucity of inclusions throughout the laccolith mass all indicate absence of assimilation. Conversely, the structural picture may be presented as a strong refutation of Reynolds' (1935) suggestion that there has been major assimilation of sediments. Our measurements show that only 10 feet of the sediments abutting against the laccolith are not directly accounted for by mechanical displacement, and the presence of the vertical fault adds plausibility to

the conclusion that the laccolith simply parted the sediments as it was intruded.

Because of this vertical peripheral fault, Shonkin Sag laccolith might be classed as a "bysmalith". The fault has such a small throw, however, that it seems unwise to apply this term to the body. The relations are not so clear in some of the other laccoliths. Square Butte and Round Butte may very likely be the remains of bysmaliths, but their peripheral contacts are not well enough exposed to prove it.

Relation of sills to laccolith.—The peripheral sills are composed of a porphyry which is the chilled phase of the magma of the laccolith. This parent magma chilled readily, producing fine-grained borders wherever it came in contact with a cooler rock. Apparently this happened even when a sill traversed shonkinite which had just crystallized, as for example at point C in Figure 7. It is inconceivable that the shonkinite here could have been very cool, since it was just the crystallized margin of the magma which ejected sill No. 5.

The fine-grained shonkinite of sill No. 1 is continuous with that of the edge of the laccolith. Sills 2, 4, and 6 are not found in contact with the laccolith. Sill No. 3 is chilled against the shonkinite of the laccolith for about 10 feet in from the contact. Similarly, it is observed to cut sill No. 2 as shown in Figure 7. Sill No. 5 cuts the shonkinite of the laccolith for about 40 feet from the periphery and then is truncated by the thrust fault. Its continuation in the overthrust mass was not observed because of weathering of the brecciated shonkinite. Sill No. 5 is also found to cut the shonkinite of sill No. 1, and its structural relationship to sill No. 2 at point A indicates that it is later than No. 2.

The border thrust.—A notable feature of the contact illustrated in Figure 7 is the thrust fault which cuts the sills. The phenomena associated with this thrust are of great significance in interpreting the history of the laccolith and have important bearing on the question of whether the laccolithic rock types were separate intrusives from the magma hearth or were formed by differentiation in place.

Unfortunately the exposure of this thrust occurs on one of the most inaccessible parts of the cliff. The outermost part of the thrust can be reached by climbing up the talus slope at the contact to the point where the thrust enters the sediments. To follow the thrust either to the right or left of this point, it is necessary to have a rope. The most significant part of the thrust is about 100 feet west of the contact, and here it forms an overhanging cliff so that one has to study the relations while spinning in space on the end of a rope. To the east, the thrust offsets sills 2

FIGURE 1. AERIAL PHOTOGRAPH OF ROUND BUTTE AND SQUARE BUTTE
Taken from the West. On Round Butte (foreground) are the lower shonkinite cliffs and the syenite cliff at the top. Note layered appearance of Square Butte.

FIGURE 2. LOST LAKE LACCOLITH
Note massive shonkinite cliffs with sills to the left.

ROUND BUTTE, SQUARE BUTTE, AND LOST LAKE LACCOLITHS

EASTERN END CONTACT OF SHONKIN SAG LACCOLITH
Showing sedimentary roof, floor, and abutment with peripheral sills.
(Photograph by W. J. Mead)

and 3 and then rapidly dies out in imbricate thrusts which in turn pass into folding.

To the west, the thrust cuts the shonkinite of the main mass of the laccolith, and its surface is marked by well-developed slickensides indicating that the direction of movement was outward from the center of the laccolith. (Movement on the thrust occurred at an angle of about 30 degrees to the plane of Figure 7, so that the dip of the fault is somewhat steeper than the projection on that plane.) The shonkinite below the thrust is massive but above the thrust it is highly fractured into irregular blocks which have moved slightly against each other, as shown by the ubiquitous slickensides. This brecciation is very obvious because the fractures are commonly filled with a light-gray phonolite. In a few cases, the phonolite is internally slickensided, indicating that it filled these fractures while movement was still continuing.

Farther west, the thrust flattens until it is almost horizontal and soon thereafter it becomes impossible to follow. At this locality the fracturing in the shonkinite of the overthrust mass disappears and a prominent flow banding is observed, trending as shown in Figure 7 (point B).

Fifty-five feet above this point occurs the abrupt end of an 8-foot syenite stringer similar in appearance to the aegirite syenite. Again the exposure is on a vertical to slightly overhanging cliff which, however, can be reached easily from above with the aid of a rope. The nature of this abrupt termination of syenite is shown in Figure 7. The 8-foot stringer intrudes the shonkinite blocks and in 20 feet laterally pinches out into four sills, each about 6 inches thick. These in turn rapidly bifurcate, and the thin syenite stringers pass laterally into the phonolite which fills the interstices of the shonkinite block fractured in the thrusting movement.

Here we come to a point very crucial in the interpretation of the laccolith. It has been shown that the syenite and phonolite locally intruded the shonkinite at the time of the thrusting. Was this intrusion of syenite the cause of the thrusting? The volume of the aegirite syenite is far too small to account for the volume increase of the laccolith. This aegirite syenite is intimately associated with the transition rock and the main syenite, so either one of these might be suggested as concomitant injections. Does this local injection of syenite into shonkinite prove that a separate mass of syenite was forced into the laccolith from below, spread horizontally under the crystalline top of the laccolith, and caused the outward thrust by its pressure?

The relations observed here seem to refute this. In the first place, if the thrust were caused by the excess pressure of the syenite, then it would be expected to occur at the elevation of the syenite and not far below it,

because the maximum shear stress due to such an intrusion occurs at its terminination. Second, the flow banding in the shonkinite at the point where the thrust dies out indicates that the shonkinite itself transmitted the pressure which caused the thrusting. Third, the syenite fills even the smallest fractures in the shonkinite, but at no point does it transgress the borders of the laccolith and send syenite stringers out into the sediments as might be expected if the syenite had considerable excess pressure.

Closer examination of the brecciated shonkinite shows that some of the larger fractures are filled with chilled shonkinite. In many fractures there was apparently an intimate mixture of shonkinite and syenite magma forming a fine-grained rock of intermediate composition. All gradations between the light-gray phonolite and the augite-leucite porphyry can be observed.

These considerations point toward the conclusion that a surge of magma entered the laccolith after the shonkinite had largely crystallized and differentiated to form the syenite. The increased pressure on the laccolith was largely dissipated by the increase in volume due to the outward thrust. This movement brecciated the shonkinite near the boundary and caused the more fluid syenite to inject locally the shonkinite. The role of the syenite seems to have been passive. It did not actively cause any displacement of the shonkinite which can be identified as separate from the movement accompanying the thrusting but it filled those fractures which the shonkinite was too viscous to occupy.

If this conclusion as to a later magmatic surge be correct and it be assumed that the parent magma had not changed much in composition during the relatively short time necessary to partially crystallize this small laccolith, then one would expect to find near the center of the laccolith a mass of shonkinite not very different from that of the original injection. It might be expected that since crystallization had progressed so far in the laccolith this last injection would not have time to differentiate.

Such a mass of shonkinite was actually found and is described on page 1054. Measurement of its specific gravity showed that it was almost identical to the undifferentiated shonkinite near the bottom and top of the laccolith.

While none of the structural details present absolute proof that the syenite was not emplaced by separate injection from an external source, in the aggregate they seem to the writer to present difficulties which in the aggregate assume considerable significance. On the other hand, all these structural details fit nicely into the picture of auto-injection, and the discovery of the late injection of undifferentiated shonkinite into the

already differentiated mass of the central part of the laccolith indicates that auto-injection must have occurred.

LOST LAKE LACCOLITH

Although the cliff exposure of the contact of Lost Lake laccolith is not so complete as in Shonkin Sag laccolith, it nevertheless presents some

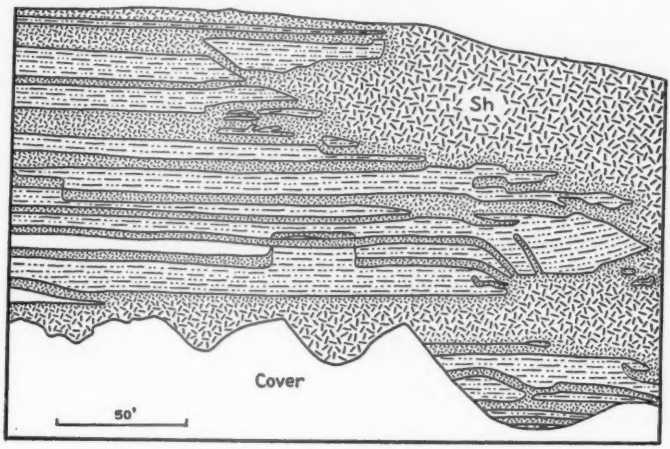


FIGURE 8.—*East end contact, south side, Lost Lake laccolith*

Igneous rock, check; sedimentary bedding indicated by broken lines.

very interesting evidence concerning the development of laccoliths. Figure 8 depicts the exposure on the south cliff of the "Sag" tributary which fortuitously cuts through the edge of this laccolith. This is the best example in the region of the complex of laccolith and peripheral sills. This exposure of the end contact shows only a negligible amount of up-bending of the sediments, which suggests that here a major part of the laccolith boundary was made up of peripheral faulting with concomitant injection of fringing sills. It exhibits many of the sill irregularities which will be described later.

Figure 2 of Plate 2 shows the contact on the opposite (north) wall of the valley of Lost Lake. Here, only a few hundred yards away and on the same horizon, the contact is vastly different. The laccolith grew to its present size in three major magma surges, each time assuming the familiar form of vertical edge with sill abutments. The first end (at A) duplicates in large measure the conditions observed at the eastern contact of Shonkin Sag laccolith, as shown in Figure 9. Here we find the

typical interfingering sills, the up-bending of the sediments, and even the outward thrust. In this case, although the genetic relation of the thrust is not so evident as in Shonkin Sag laccolith, there are some indications that it was formed in a similar manner but a little earlier in the development of the laccolith. The thrust continues into the main shonkinite

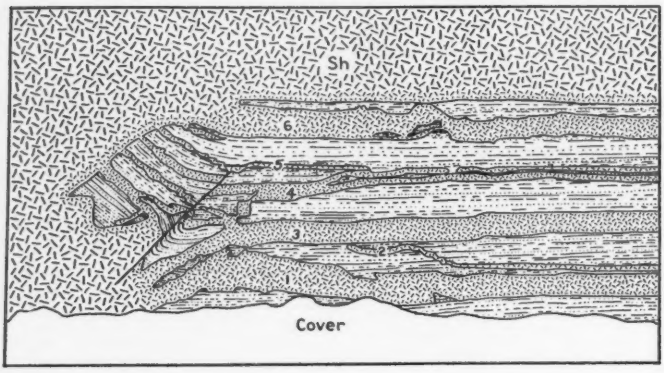


FIGURE 9.—*Detail of point A in Figure 2 of Plate 2*

Showing peripheral sills (numbered), thrust, bending, and later truncation by the second major magma surge.

to the left but soon fades into a slight flow banding. There is also some evidence of brecciation of the shonkinite, and the fractures are filled with porphyry and a fine-grained, light-colored rock which may be phonolite or may be only the interstitial liquid of the mushy shonkinite which was squeezed out to fill these fractures. In any event, this thrusting was apparently accompanied by the ejection of sill No. 5 (Fig. 9) which by its irregularity and rapid lateral termination (Pl. 11, fig. 2) gives evidence of high viscosity.

Shortly after this episode, a second major surge of magma caused the shonkinite magma to cut upward across the sediments in the upper left of Figure 9 and spread out laterally until it finally ended with the typical sill abutment at point B in Figure 2 of Plate 2.

Slightly later the third major pulse of magma cut across this newly formed end and surged outward, truncating the sills at point C, and apparently ended in the usual style where the little gully may be seen in the photograph. The weakness which localizes this gully is characteristic of the laccolith ends, where the shonkinite is commonly weathered and very rotten, presumably because of the brecciation.

This evidence of major surges in a pulsating injection supports the conclusion already advanced that the thrusting in Shonkin Sag laccolith was caused by a later surge of shonkinite, albeit much smaller in volume than these great surges, each of which may have doubled the volume of Lost Lake laccolith.

COWBOY CREEK LACCOLITH

Two miles to the north and west of Square Butte there is a highly faulted structural basin, so complexly deformed that its structure was

FIGURE 10.—*Cross section through Cowboy Creek laccolith along stream incision*

Vertical exaggeration of two. Length of exposure—2000 feet.

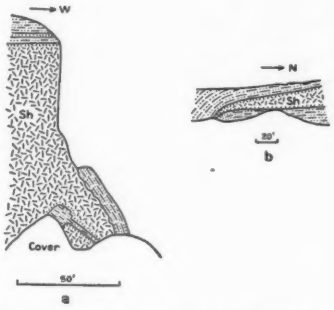


FIGURE 11.—*End contacts of Minor laccolith*

not worked out beyond the generalization from the stratigraphy that beds of Judith River and Claggett formations have been downfaulted into this sharply bounded basin. Two laccoliths are intruded at the edge of this zone of deformation and are evidently post deformation. These two—the Minor laccolith (across the "Sag" from Shonkin Sag laccolith) and the Cowboy Creek laccolith (about two miles northwest of Square Butte)—have the most irregular and variable peripheral contacts observed in the region, presumably because they were intruded into deformed sediments.

Figure 10 is a diagrammatic cross section through the Cowboy Creek laccolith taken along the south-central gully which exposes a complete section through the laccolith, showing top, bottom, and both peripheral contacts. The asymmetry shown in this section is characteristic of the laccolith as a whole and is reflected in the plan as shown in Figure 2. The shape of the laccolith seems to have been controlled by the preexistent fold which now forms its eastern border.

Since this laccolith lies right on the strike of the last good exposure of the "ductolith", its outlines were investigated thoroughly in the mag-

netometer survey undertaken to determine whether this horizontal pipe acted as a feeder for the laccolith. As will be shown later, this survey proved that the "ductolith" is not the feeder and indicated the presence of a vertical pipe.

MINOR LACCOLITH

Like the Cowboy Creek laccolith, the Minor laccolith seems to be irregular in outline, but its peripheral contacts are covered except for two exposures so that only meager information about its shape is available. These two contacts are figured in Figure 11. Figure 11a closely resembles the eastern contact of Cowboy Creek laccolith, except that it seems likely that here vertical faulting has displaced the sediments past the vertical cliff. Figure 11b somewhat resembles the pinching out of Cowboy Creek laccolith on the western edge. The Minor laccolith was apparently intruded into the edge of the distorted basin, but its structural dependence is not so clear because of lack of exposures.

SQUARE BUTTE LACCOLITH

The peripheral contact of the largest laccolith was observed in three places. On the southeast corner of Square Butte a small valley follows the contact for a few hundred yards. Here the sediments lie concordantly on the chilled shonkinite and dip outward at an angle of about 30 degrees. Farther north, on the eastern side, the gently dipping sediments abut directly into the shonkinite which has a nearly vertical contact. Still farther north, the contact is not exposed, but sediments with intercalated sills occur in a valley wall opposite a cliff of shonkinite in a manner which can only be explained by a contact of the usual sill abutment type. On the western side of the laccolith the contact is exposed in several small gullies, and here the sediments are very sharply upturned against the laccolith. This upturn seems to occur mostly in the few hundred feet adjacent to the laccolith, and right near the contact the sediments are nearly vertical.

The outline of Square Butte laccolith is sharply marked in many places by a rampart seemingly held up by the more resistant chilled border. Aerial photographs show this encircling rampart much more clearly than it can be observed on the ground and permit an accurate reconstruction of the shape of the laccolith as shown in Figure 2.

Along the western margin of the laccolith a dike of syenite cuts through the shonkinite approximately parallel to the contact. This dike, which is several feet thick but highly irregular, occurs several hundred feet below the usual level of the syenite-shonkinite contact and seems to be analogous to the phonolite stringers of Shonkin Sag laccolith. Above it, on the northwest comb of the butte the marginal irregularities of the

SYENITE-SHONKINITE CONTACT

Local intrusion showing large-scale auto-injection near periphery of Square Butte. The dark rock is shonkinite.

FIGURE 1. TOP OF PERIPHERAL CONTACT
On west ridge of Shonkin Sag laccolith. Chilled shonkinite in lower right-hand corner. Note bending and outward thrusting of sediments.

FIGURE 2. SILL AT LOST LAKE LACCOLITH
Showing round-nose end and second finger (to right).

WESTERN CONTACT OF SHONKIN SAG LACCOLITH AND SILL END AT LOST LAKE

syenite-shonkinite contact are particularly well exposed. Plate 10 shows how the syenite locally intrudes the shonkinite. At the time this motion occurred, the shonkinite was solidly crystalline for a few hundred feet from the border but toward the center of the laccolith it was only partially crystalline, and a considerable amount of mixing of the magmas occurred.

Thus, the observed local injection of syenite into shonkinite took place at about the same relative time in the history of Square Butte laccolith as that in Shonkin Sag laccolith. The absolute time interval since the beginning of laccolith development was much greater, however, because it was a larger mass. In the theory of auto-injection this fact presents no special situation. It would be supposed that magma surges continually enter the mass, at intervals whose spacing makes little difference. The early surges build up the laccolith with the concomitant ejection of peripheral sills. The later surges would cause some motion of the already differentiated magmas. Thus, we would not expect to get auto-injection of syenite before crystallization of shonkinite had progressed considerably, and we would not get auto-injection after the laccolith had completely crystallized.

Although this occurrence of local injection at the same relative time in the two bodies is to be expected following the theory of auto-injection, it requires a special coincidence on the hypothesis of separate injection. While one might readily expect a series of injections of the various rock differentiates from a magma reservoir, these would be expected to enter the laccoliths indiscriminately and not to enter each at just a certain phase of its history. This coincidence in time, while not of cardinal importance in itself, adds one more degree of improbability to the explanation of the syenite-shonkinite relations in the laccoliths by the theory of separate injection.

SIZE AND SHAPE OF LACCOLITHS

The ground plan of the laccoliths is shown in Figure 2. Four of these are sufficiently well exposed so that their shape can be established with certainty: Shonkin Sag, Round Butte, Cowboy Creek, and Square Butte. Round Butte and Shonkin Sag laccoliths are nearly circular in plan as would be expected of laccolithic intrusion from a central pipe into uniform flat-lying strata under an equally distributed overburden. The straight eastern margin of Cowboy Creek laccolith was controlled by preexistent folding as has been shown. The anomalous triangular shape of Square Butte cannot be explained by the data in hand.

Table 5 gives a comparison between the horizontal area of the laccoliths and their thickness. The observed irregularity seems to defy a theoretical

TABLE 5.—*Area and thickness of the laccoliths*

	Area (sq. mi.)	Thickness (feet)
Shonkin Sag	2.64	250
Square Butte	6.1	1500+
Round Butte	.68	700+
Cowboy Creek	.8	200
Montague	3.4 (?)	200

derivation of the relationship between area, thickness, and depth of burial in the manner that Gilbert attempted. Only one uniformity is observed: that the thickest laccoliths occur at the highest elevations. This may have been because the overburden there was significantly less.

HORIZON OF INJECTION

All laccoliths except Cowboy Creek are intruded into the Eagle sandstone of Upper Cretaceous age. This horizon has two features which make it well suited for the formation of sill-like bodies. It is a thin-bedded sandstone, easily parted parallel to the bedding, and it immediately overlies the thick Benton shale, through which a magma could push its way with a minimum of energy. In many cliff exposures the sandstone intercalated with sills is exposed, and directly under it the shale contains no sill-like bodies. It is also curious to observe that none of the exposures shows sills forming at the contact but only up in the sandstone. A very similar set of conditions is observed in the Henry Mountains laccoliths.

THE FEEDER

Although a hypothetical pipe is drawn in every cross section of a laccolith described in the literature, the writer knows of no exposed pipe which can be shown to have been the feeder for a laccolith. With this specific problem in mind, the writer searched many of the laccoliths in the Highwood, Bearpaw, Little Rocky, Judith, and Moccasin mountains of Montana, the outlying domes of the Black Hills, and the northern laccoliths of the Henry Mountains; nothing resembling a vertical feeder was found.

It is interesting that three of the most different possible types of feeding conduits are exposed near the Highwood laccoliths:

(1) Haystack Butte shows a pipe-like body at the junction of two dikes. This apparently represents the intersection of two tension fractures and consequently presents difficulties as a feeder for laccolith, since it seems likely that tension fractures would tear through the relatively brittle Eagle sandstone and the magma would erupt to the surface.

(2) On the ridge less than a mile west of Shonkin Sag laccolith are three pipes whose form suggests that they were intruded by forcible injection (Fig. 12).

(3) Extending from the Highwood Mountains toward the Cowboy laccolith, in the shadow of Square Butte, is the curious body which Buie calls the "Headed Dike", but which the writer prefers to term the "Ductolith", hoping that this barbarous mixture of Latin and Greek will call attention to its interpretation as a frozen magma conduit. This body has four characteristics which suggested to the writer that it might be a laccolith feeder:

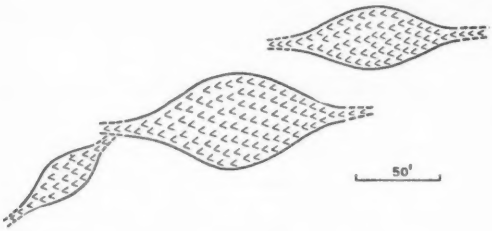


FIGURE 12.—*Pipes in flat-lying sediments*

On ridge one mile west of Shonkin Sag laccolith (plan).

(a) Evidence of its high temperature: abundance of large leucite crystals; the magnitude of alteration at its sedimentary contact—greater than that produced by any of the laccoliths; and the lack of a chilled border.
(b) Its shape: rounded top, tear-drop section, as one would expect for a light magma flowing horizontally through flat-lying, easily deformed sediments.
(c) Its direction and extent: outward from the Highwood mountain mass for a distance of 3½ miles (exposed) toward the laccoliths.
(d) At its last exposure it passes under a Tertiary bench. At the opposite side of the bench, 1½ miles away, and directly in line with the strike of the "ductolith" lies the Cowboy laccolith.

The Geophysical Section of the United States Geological Survey very kindly undertook a magnetometer survey of the Shonkin Sag and Cowboy Creek laccoliths to determine whether the sharp magnetic contrast between the shonkinite and the enclosing sediments might permit the detection of feeders for the laccoliths. In particular, it was thought that the possible connection between the "ductolith" and the Cowboy Creek laccolith could be verified or disproved by a magnetic survey across the Tertiary bench mentioned above. The results of the magnetic survey will be reported in a separate paper by Mr. E. L. Stephenson, who had charge of the geophysical work.

In brief, Stephenson's studies show the presence of certain magnetic anomalies which are of considerable interest in connection with the location of possible feeders. The "ductolith" was followed for 1½ miles under the Tertiary bench but it curved away from the laccolith and was shown to have no connection with it.

SILL IRREGULARITIES

General statement.—The peripheral sills are in general strikingly uniform; and when traced for many hundreds of yards along the cliff face of the Sag show no significant change in thickness or texture. However, in contrast to this general regularity, there are very striking localized irregularities. A sill may be traced with no change for some distance and then abruptly end. Its end is in the form of a round nose,

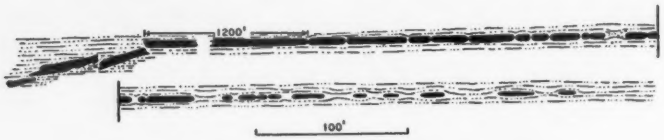


FIGURE 13.—*Sill No. 5 at Shonkin Sag laccolith*

with no entering wedge of magma to split the sediments as it was intruded. An example of this type of end is shown in Figure 2 of Plate 11. If the sill has been uniform up to this point, it generally does not terminate here completely, but may be picked up farther along the same horizon or on another horizon. In Figure 2 of Plate 11 the sill which ends in the left half of the picture may be seen to recur on the same horizon in the right half. Figure 13 shows the irregularities of sill No. 5 of the Shonkin Sag laccolith. (See Figure 7.)

These irregularities show that the periphery of a sill as it is injected is not a smooth circular wedge but is highly serrate and is composed of many fingers, each of which ends in a "round nose". Perfect examples of this type of sill ending are found in the rhyolites of the Homestake gold mine. Through the courtesy of the Homestake Mining Company, Figure 1 of Plate 12 is reproduced to show one of these.

As more magma is forced into the central portion of the sill, these fingers are ejected, moving in the direction of their elongation, gradually spreading laterally at the same time, until they meet and join to form the continuous central disk of the sill. A by-product of this enlargement of the fingers is the distortional effect on the sediments immediately above and below. Owing to the viscous drag of the sill magma and the stress set up at the round nose, the sediments are shoved ahead of the fingers as seen in section in any vertical plane and fill the gap made by the parting of the sediments. Then, as the two fingers join, they squeeze between them a ridge of contorted sedimentary material. A ridge of this type is shown in section (Pl. 12, fig. 2). Again, the Homestake rhyolites show this relationship better (Pl. 13).

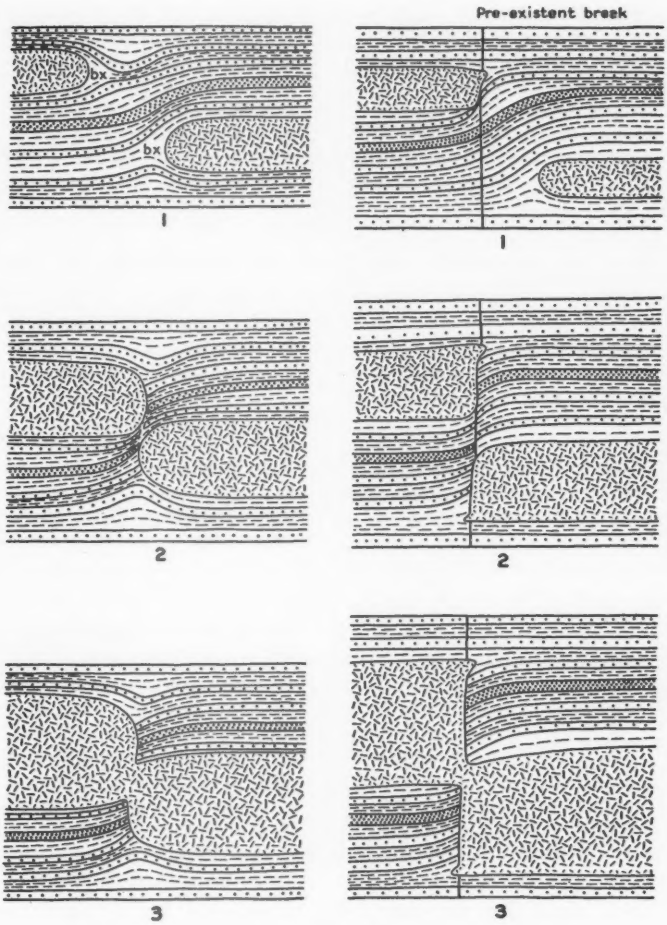


FIGURE 14.—*Successive stages of two types of sill offsets*

(A) Round-nose offset, (B) Dike-fault offset. Igneous rock stippled. *Bz* indicates brecciated zone.

Sill offsets.—Fingers of the sill may crosscut the sediments somewhat in their development. As two fingers on different horizons spread laterally to form a sill, an offset in the sill is formed where they meet. Two types of offsets have been recognized, both in the Highwood Mountains area and in the Homestake Mine, where Mr. James A. Noble kindly

permitted the writer to examine relations that the geologic staff had determined. The development of these two types of structure, termed "round-nose offsets" and "dike-fault offsets", are depicted in Figure 14. Most of the irregularities in the sills of the Highwood area are found to be some stage in the development of fingers or offsets. It is suggested that these irregularities are characteristic of dike and sill injections in general.

DEVELOPMENT OF THE LACCOLITHIC DISK

(A hypothetical reconstruction of the history of Shonkin Sag laccolith)

The first event in the development of Shonkin Sag laccolith was the intrusion of sill No. 1—a 34-foot sill which extended for many hundreds of yards beyond the periphery of the present laccolith. This was injected as an ordinary sill and maintained its thickness with little change as it spread outward, showing that the magma was relatively fluid, with slight tendency to dome the overlying sedimentary rocks.

Sill No. 1 expanded horizontally until its edges were so chilled in passing through the sedimentary rocks that crystallization began, thus putting an end to further lateral expansion. As this crystallization proceeded inward, pressure gradually increased in the central part of the sill. Finally, when the pressure exceeded the strength of the confining rocks, it broke its way out. The central disk of the sill was at this time under hydrostatic pressure, but the crystalline outer part exerted no pressure on the surrounding rocks. There was thus a stress concentration where the change from liquid to solid occurred. The nature of this stress concentration can be analyzed as follows: The molten central disk pushed on its roof as on a piston, tending to punch out a disk of sedimentary rocks above it. The sedimentary rocks did not act as a rigid piston, however, but bowed up slightly over the central disk. This arching introduced tensile forces which may have been the most important factor in the peripheral fracturing which provided the channelways for the ejection of the later sills. The doming roof was subject to tensile forces throughout, but the downward concavity in the central part produced a compressive component partially counteracting the tensile force. At the edge, however, where the molten magma abutted on the solid sill, there was a point of inflection where the sediments were convex downward. This produced a maximum of tension where the downward convexity was greatest. Consequently, a circular fracture formed, and the central disk rose under the hydrostatic pressure of the magma beneath. Owing to the downward convexity of the sediments at the locus of fracture, the resultant fractures would tend to gape downward, and the magma, instead of bursting through to the surface, split the sediments and injected sill No. 2. From this time on, the edge of the central disk was a zone of weakness

FIGURE 1. ROUND-NOSE OF HOMESTAKE RHYOLITE DIKE

FIGURE 2. INTERFINGER RIDGE OF CONTORTED SEDIMENT
Shonkin Sag laccolith.

SILL IRREGULARITIES

THREE FINGERS OF HOMESTAKE RHYOLITE

from which the later sills were shot out into the sediments; No. 3 followed No. 2 and was followed by No. 5. The relative ages of Nos. 4 and 6 are uncertain.

A long interval of time elapsed between the injection of sill No. 1 and sill No. 5. This is shown by the fact that sill No. 5 cuts through the crystalline shonkinite at the end of the laccolith for a distance of 40 feet from the edge, and is chilled against it.

After a further lapse of time when the laccolith had solidified completely about 60 feet from the edge and after considerable differentiation had taken place, a mass of shonkinite magma was intruded into the center of the laccolith from the source, indirectly causing the outward thrusting shown in Figure 7. Because of the lower viscosity of the syenite magma at this time, it moved more freely than the partly crystallized shonkinite and caused considerable auto-injection of syenite into the shonkinite near the margin of the laccolith, thus providing the structural relations which Barksdale assumed to prove a later injection of syenite from an external source.

The series of sills suggests a pulsating injection of magma. It is easily possible, however, to account for these relatively minor volume increases without resorting to pulsating injection. Two things would act in a manner tending to produce this effect: (1) The bending of the roof might tend to act as a potential reservoir to store up enough magma to form one sill. Then, when the pressure was released by fracture of the sediments and the sill ejection, the sediments might tend to return to their horizontal position as a result of their elasticity and weight. (2) Viscous friction along the conduit might retard the flow of magma from the source to the laccolith. Thus when a peripheral fracture opened and a sill was formed, the pressure in the laccolith might fall suddenly and be only gradually regained, when the cycle would be repeated.

It seems impossible, however, to account for the large volume increases shown at Lost Lake when the magma broke over from point A to point B, and later to point C (Pl. 2, fig. 2), without assuming a major surge of magma emanating from the source. It is also thought that the last injection at Shonkin Sag (producing the thrusting) was of this nature. Such pulsating ejection from a magma source is characteristic of the Henry Mountains laccoliths and is common in volcanoes.

EXPERIMENTAL LACCOLITHS

In order to test the ideas outlined above as to the mechanism of injection and the reactions of the sediments, some crude experiments were performed in which the attempt was made to simulate the conditions thought to exist in the case of Shonkin Sag laccolith.

In these experiments, a basin 20 inches in diameter was used. The bottom was filled with plaster of Paris to make it rigid, and a pipe fitting was left projecting slightly. On the other end of this pipe was an alemite fitting. Sediments were then deposited over the plaster of Paris, and

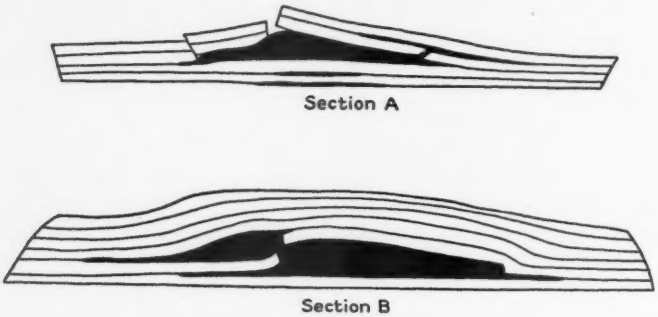


FIGURE 15.—*Sections of experimental laccoliths*

artificial magma was introduced through the pipe by means of a grease gun.

The major problem in experimentation of this sort is to choose the sediments so that they have a strength and coherence commensurate with their scaled-down extent and thickness. A test which may be applied here is that they will hold their own weight over an arch which is the scaled-down equivalent of the arch which the natural sedimentary rocks will support. In the writer's experiments, this condition was only roughly achieved.

A second problem was the choice of a magma analogous to natural magmas. Paraffin was first tried, but it does not have a sharp crystallization point and in the region of solidification it is very plastic rather than easily broken as are igneous rocks. After some experimentation, stearic acid was chosen as the most practical magma. It is cheap, has a sharp crystallization point, its melting point (69.2° C.) is in the region of easy experimentation, and it crystallizes sufficiently slowly in sediments at room temperature to permit easy handling and at the same time to produce the effects of chilling which are noted in the real laccoliths.

Two sections of experimental laccoliths are reproduced in Figure 15. These have little similarity to the real laccoliths but are thought to show some of the principles believed to have been operative. Section A shows paraffin intruded into brittle plaster of Paris layers separated by a part-

ing of grease. Here the outward-sloping fractures are seen to have developed, and the one on the left shows thrust faulting. It is also seen that a thin sill extends outward from the point at which this fracturing occurs.

Section B shows a stearic acid laccolith intruded into plasteline layers with a strength more nearly commensurate to the conditions of the Highwood laccoliths scaled down. This laccolith evidently developed first as a sill which followed through the hypothetical first part of the history of Shonkin Sag laccolith, ending with the development of a peripheral fracture presumably at the liquid-solid contact in the sill. The vertical peripheral fault on the right duplicates the steep normal fault of Figure 7. On the left, the fracturing took place at the point of maximum downward convexity of the sediments, and the magma was forced out through this downward gaping fracture to form the secondary laccolith on the left flank, which is analogous to sill No. 4 in Figure 7.

Another feature of interest in these experiments is the fact that the laccoliths and sills have serrate edges, similar to the fingering edges of the sills at Shonkin Sag laccolith, but the fingers are much more stubby. Further, it was observed that during the injection of the magma the resistance to injection periodically increased, presumably as a sill crystallized and hindered further lateral spreading. Then, as the pressure on the magma was increased, it would fracture the sediments and permit more magma to be intruded, either in the central disk or in peripheral sills. This seems directly analogous to the pulsating injection suggested for the natural laccoliths.

SUMMARY

The general structural relations of the Highwood Mountains laccoliths are described, illustrating a type of laccolith quite different from Gilbert's classic examples. Hurlbut has shown that study of these laccoliths provides petrologic evidence that each one has differentiated in place, producing its own syenite and shonkinite. Detailed structural study indicates that local intrusive relations which have been interpreted by Barksdale as proving separate injection of syenite from the magma source are more easily explained as due to auto-injection.

Lost Lake laccolith provides evidence that the laccoliths may be formed by a series of magma surges from the reservoir below. Here the later surges are shonkinite varying only slightly in composition from the original magma. This lends plausibility to the conclusion that the later magma surge which caused the outward thrusting and auto-injection of syenite in Shonkin Sag laccolith was also shonkinitic in composition.

The peripheral sills, although very regular in general, show local irregu-

larities which have been analysed as due to the advance of the serrate edge of the sill as it grew. The sills are observed to end in round noses rather than in magma wedges. Two types of offsets are described: (1) round-nose offsets, and (2) dike-fault offsets.

The detailed structural study permits a hypothetical reconstruction of the development of the laccolith. To provide graphic illustration of some of the processes involved, artificial laccoliths were formed in the laboratory by the injection of stearic acid into artificial sediments. These experimental laccoliths duplicated some of the features observed in the Highwood Mountains laccoliths, notably the peripheral sills and the outward thrusting. They also illustrate one possible type of pulsating injection.

The fundamental problem of the pipe-feeder is considered. Three types of pipes are found in the region, and their merits as laccolith feeders are discussed. This suggested the desirability of a magnetometer survey of some of the laccoliths in the attempt to locate the feeders.

SEPARATE INTRUSION VERSUS DIFFERENTIATION IN PLACE

INTRODUCTION

It is an interesting fact that two parties studying in detail a well-exposed intrusive and using similar field and laboratory methods can arrive at diametrically opposed conclusions as to the origin of the rock types found in the body. It seems desirable for that reason to examine the specific differences in the observations and to state clearly the nature of the arguments which support the hypothesis of differentiation in place.

DIFFERENCE IN OBSERVATIONS

The Harvard party began the study of Shonkin Sag laccolith shortly before Barksdale and continued this study independently for 3 years. Due largely to the broader scope of the Harvard study and to the fact that roughly twice as many man-hours were spent in the field, the Harvard group was able to make some observations not recorded by Barksdale.

The greatest single difference between the writers' observations on Shonkin Sag laccolith and Barksdale's is in the density determinations. Barksdale observed an upward increase in density through the lower shonkinite in three out of five sections. One of these two anomalous sections is in a place where it is impossible to get fresh rock, except by blasting, so it is discarded in the present discussion. The other is in a place fairly difficult to climb, and great care must be taken to obtain fresh samples. Here the writers' determinations of 1935 differed from Barksdale's, so the measurements were remade in 1938. It was found

that the new measurements checked with the old ones and showed the uniform increase in density from bottom to top of the lower shonkinite. Two measurements of sections not recorded by Barksdale show the same uniformity. Further, Barksdale does not mention the downward decrease in density of the upper shonkinite, noted by Osborne and Roberts and confirmed by the writers' measurements, which is equally important to the theory of differentiation in place.

The second difference in observations on Shonkin Sag laccolith is the detailed structural study of the end contact and the local intrusion of syenite into shonkinite. By the use of a rope sling, many points on the cliff were studied which are not mentioned by Barksdale. Since the intrusion of the syenite into the shonkinite is one of the strong arguments for separate injection, these structural relations are crucial because of their suggestion that this local intrusion was due to auto-injection rather than to separate injection of syenite from an external source.

The main difference in data, however, is in the fact that the Harvard studies were not restricted to one laccolith but included all the laccoliths of the region. All of them contain syenite and shonkinite. The syenite of the small laccoliths is of the order of 5% of the volume of the laccolith, its composition differs very little from that of the shonkinite, and the shonkinite itself does not contain so high a proportion of heavy minerals as in the larger laccoliths.

The syenite of the intermediate laccoliths (Shonkin Sag, *eg.*) is about 10% of the volume of the laccolith and is more highly differentiated from the shonkinite than in the smaller laccoliths. The lower shonkinite contains a higher proportion of dark minerals, but they have not reached a close packing.

The largest laccolith (Square Butte) contains about 40% of the most highly differentiated syenite. This syenite within itself shows differentiation with more mafic lower layers. The dark minerals in the lower shonkinite seem to have reached a maximum of close packing, giving the rock a high, uniform density.

Heavy-mineral separations in Shonkin Sag and Square Butte laccoliths show that in a columnar section the average percentage of heavy minerals through all the rock types checks very closely with the percentage of heavy minerals in the chilled phase of the shonkinite.

NATURE OF THE ARGUMENT

Barksdale's strongest arguments for separate injection are the abrupt contacts and the local intrusion of one rock by another. Such relations are not only compatible with the theory of differentiation in place, they are to be expected. At the top of the lower shonkinite, crystals settled

from above to form a zone of close packing with a well-defined upper limit. The upper shonkinite-syenite contact is the locus below which cooling from the upper sedimentary surface was too slow to prevent removal of the phenocrysts of dark minerals. This contact is normally gradational, but a sharp irregular contact is found in places due to auto-injection. The contact of syenite and transition rock formed at the bottom of the zone enriched in leucite. A fluid magma existed below a nearly consolidated syenite, and thus a late movement in the laccolith caused local injection of syenite by transition rock. The lower contact of the transition rock marks the break that existed between the crystalline rock below and the fluid magma above.

Barksdale postulates the injection of syenite and pegmatite magma into rock that was partially liquid. Under such conditions, the problem would be not to explain the gradational contacts but to account for the fact that they are not more gradational than those observed. If there were a centrally located pipe, thin sheets of syenite and pegmatite magmas must have been forced for over half a mile in all directions between unconsolidated walls. It is highly improbable that such a process could have taken place without considerable commingling of the magmas. The theory of separate injections, therefore, appears to disagree with one of the main arguments on which it was based.

On the other hand, it seems impossible to set up criteria which can unequivocally prove the hypothesis of differentiation in place. This is due to the fact that most things which are accounted for by such a hypothesis may also be explained by setting up special conditions of separate intrusion. For example, Barksdale would explain the uniform upward increase in density of the lower shonkinite by an intrusion which became progressively more femic. This alone is not improbable, but, when it is necessary to suppose just the opposite to account for the density distribution in the upper shonkinite, the improbability of the whole increases.

The larger the laccolith the greater is the proportion of syenite and the more advanced the chemical differentiation between the rock types. This is to be expected from the theory of differentiation in place, but for the hypothesis of separate injection it requires a very special set of conditions for each laccolith. Thus, while any detail may be adequately explained by the hypothesis of separate injection, each additional similar occurrence calls for further special conditions until the whole becomes a pyramid of special hypotheses.

The hypothesis of differentiation in place must, therefore, be supported not by clear-cut proofs but rather by the accumulation of evidence for the whole region. All the data assembled—physical, chemical, struc-

tural, and petrological—are in agreement with the simple hypothesis that a homogeneous parent magma was intruded into each laccolith, where differentiation took place according to the size of the laccolith.

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FIGURE 1. YEAGER GREENSTONE CAPPED BY CAMBRIAN SANDSTONE (Et.)
Northern end of Mazatzal Range.

FIGURE 2. RED ROCK RHYOLITE
North side of Deer Creek, Mazatzal Range.

FORMATIONS

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PRE-CAMBRIAN MAZATZAL REVOLUTION IN CENTRAL ARIZONA

BY ELDRED D. WILSON

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ABSTRACT

The Older pre-Cambrian rocks of central Arizona are divided, in chronological order, into the Yavapai group (previously termed the Yavapai and Pinal schists); Deadman quartzite, Maverick shale, and Mazatzal quartzite; small intrusive bodies; and batholithic masses of granite. A great unconformity separates these rocks from the Younger pre-Cambrian Apache strata.

The Yavapai group is subdivided into the Yaeger greenstone, Red Rock rhyolite, and Alder sedimentary series. These formations are definitely schistose only near intrusive bodies.

In the Older pre-Cambrian rocks the principal regional structures are folds and normal and reverse faults of subparallel, northeast to north trend and shear and normal faults that strike north to west. The folds show northwest to west overturn and northeast to north plunge. The dip of the reverse faults varies from a few degrees to more than 80 degrees southeast.

It is concluded that the principal structures in the Older pre-Cambrian rocks resulted from one profound crustal disturbance—the Mazatzal Revolution—which took place after the Mazatzal quartzite, and long before the Apache strata, were laid down. Marked by intense northwestward compression and culminating with the batholithic invasion of the only pre-Cambrian granite recognized in the region, this revolution doubtless gave rise to a huge range, the roots of which are unconformably overlapped by Paleozoic strata.

INTRODUCTION

As indicated by the Geologic Map of Arizona (1924) formations of known or supposed pre-Cambrian age constitute about half of the visible rocks in the State's numerous widely distributed mountain ranges, most of which are separated by basins floored with Tertiary and Quaternary beds. Classic examples of so-called Archean and Algonkian types crop out in the Grand Canyon.

Arizona's greatest exposures of pre-Cambrian sedimentary and volcanic rocks are in the central mountain ranges, within 90 to 200 miles from the Grand Canyon. This central region has yielded approximately $500,000,000 worth of copper, gold, silver, lead, and zinc, mainly from the Jerome pre-Cambrian deposit and partly from numerous Laramide veins in pre-Cambrian host rocks whose salient controlling structures appear largely to be heritages from pre-Cambrian deformation.

The pre-Cambrian geology of some areas near this central region have been studied in detail, such as the Globe (Ransome, 1903), Ray-Miami (Ransome, 1919), and Bradshaw Mountains (Jaggar and Palache, 1905). Within the region, the Jerome and other districts have received consid-

erable attention from geologists, but the locally complex relations, augmented by rough, brushy country, have made regional separation, correlation, and structural analysis rather difficult. As long as the broader relations of the several pre-Cambrian formations remain unknown, the local stratigraphy and structure are interpreted diversely.

Lindgren (1926, p. 20, 56; 1930, p. 462) has emphasized the difficulty of separating the greenstone and sedimentary schists, which are the two oldest formations exposed in the region. In other words, a large element of the structural study is the definition of the formations. Broad conclusions regarding such ancient formations are inevitably based to a disquieting extent upon assumptions.

FIELD WORK AND ACKNOWLEDGMENTS

It seemed highly advantageous to supplement the available information by further studies in central Arizona. A complete study would consume many years, and consequently certain strategic areas were chosen for special investigation. These districts (Fig. 1) are, from northwest to southeast, the Del Rio area, southern Black Hills, Pine Creek area, Mazatzal Mountains, and the eastern part of the Tonto Basin.

This investigation was begun in 1930, after discussions of the pre-Cambrian rocks in the Jerome and Black Hills districts by Lindgren (1930) and Lausen (1930) indicated the need for an understanding of the regional structure. The field work occupied approximately 6 months, distributed over widely scattered intervals until late 1935. It was begun as a research problem for the Arizona Bureau of Mines, whose generous support was supplemented in 1933 by a grant from the Penrose Bequest of the Geological Society of America.

The members of the Department of Geology of Harvard University, especially Professors Kirk Bryan, Marland Billings, Russell Gibson, L. C. Graton, and D. H. McLaughlin, gave many constructive suggestions regarding the scope of the work and the organization of the data. Professor Gibson spent several days examining the field relations during the summers of 1932 and 1934. Acknowledgments are also due Dr. G. M. Butler, Director of the Arizona Bureau of Mines, for encouraging this research, and Professors B. S. Butler, M. N. Short, and A. A. Stoyanow, of the University of Arizona, for valuable suggestions.

TOPOGRAPHY

The areas studied lie within a portion of the Basin and Range Province about 100 miles long by 15 to 50 miles wide (Fig. 1) bordering the southwestern margin of the Colorado Plateau.

The principal features of relief are the Sierra Ancha, Tonto Valley, Mazatzal Mountains, Verde Valley, Black Hills Range, and Lonesome Valley, all of which trend northwestward. Each of the ranges exceeds 7500 feet, but none are more than 8000 feet in altitude. They are 30 to

50 miles long by 12 to 20 miles wide and approximately 25 miles apart. Their slopes are characteristically steep, rugged, and brushy. These ranges and valleys are regarded as slightly tilted horsts and grabens which were formed in Tertiary time.

ROCKS OF CENTRAL ARIZONA REGION

GENERAL SUCCESSION

As a result of the present investigation in several districts in central Arizona, the pre-Cambrian succession is interpreted as shown in Table 1. It is to be noted that the two major systems are referred to simply as Older and Younger pre-Cambrian.

The Paleozoic and later stratigraphy shown in Table 1 is according to Stoyanow (1936) and the writer, with acknowledgment of the earlier work of Ransome (1916), Darton (1925), and Jenkins (1923). These rocks are not described in the present paper.

TABLE 1.—*Formations of Central Arizona*

	Age classification	Group and formation	Character	Thickness in feet
Quaternary	Pleistocene and Recent	Alluvium	Unconsolidated silt, sand, gravel, and boulders, mainly of local origin	
		—Unconformity—		
Tertiary		Volcanic rocks	Largely basaltic and andesitic lava and intercalated tuff	0–2000±
	Pliocene (?)	Gravel, conglomerate, sand, silt, and limestone	Loosely to firmly consolidated gravel, sand, and silt, locally with thin limestone beds and intercalated basalt flows; in upper Verde Valley, predominantly limestone (Verde formation); probably synchronous with Gila conglomerate	2000±
		—Unconformity—		
	Miocene or Pliocene	Volcanic rocks	Andesitic and dacitic lava and intercalated tuff	2500±
	Miocene (?)	Conglomerate	Conglomerate and sandstone	1200±
		—Unconformity—		
Carboniferous	Permian	Coconino sandstone	Light-colored cross-bedded sandstone in Mogollon Escarpment	900–1000
		Supai formation	Reddish sandstone and shale in and near Mogollon Escarpment	645–1000
	Pennsylvanian	Limestone	Light-gray compact limestone. Thins out northwest of Pine	1000
	Mississippian	Limestone	Light-gray, partly crystalline limestone: Redwall limestone in northwestern portion of region, Escabrosa limestone in southeastern portion	50–250
Devonian		Limestone	Dark-gray thin-to medium-bedded limestone: Jerome formation in northwestern portion of region, Martin limestone in southeastern portion	300–500

	Age classification	Group and formation		Character	Thickness in feet
		—Disconformity—			
Cambrian (Middle)		Sandstone		Red-brown cross-bedded pebbly Troy sandstone in northern Sierra Ancha and southern Mazatzal Mountains areas; dark red-brown bedded friable Tapeats sandstone, 75–100 feet thick, in northwestern portion of region	75–400
Pre-Cambrian	Younger pre-Cambrian	Apache group (in eastern Tonto Basin and southeastern portion of Mazatzal Mountains)	Unconformity		
			Basalt	Vesicular, epidotized basalt, present at most places	0–75
			Mescal limestone	Thin-bedded cherty dolomitic limestone, intruded by diabase	225–300
			Dripping Spring quartzite	Reddish-brown, generally massive, fine-grained arkosic quartzite; intruded by diabase	450–700
			Barnes conglomerate	Smooth, rounded pebbles in sandy, arkosic cement; intruded by diabase	5–50
			Pioneer shale	Brownish-red hard shale; intruded by diabase	150–250
			Scanlan conglomerate	Imperfectly rounded pebbles in sandy arkosic cement; intruded by diabase	0–30
		Unconformity			
	Older pre-Cambrian		City Creek series	Shale with some interbedded quartzite; stratigraphic position uncertain	2000 ±?
		Mazatzal quartzite		Light-brown to gray vitreous, hard quartzite; intruded by granite	3800
		Maverick shale		Gray to maroon shale; appears only in Mazatzal Mountains; intruded by granite	500–800
		Deadman quartzite		Light-brown to gray, vitreous hard quartzite, pebbly at base; appears only in Mazatzal Mountains; rests unconformably on Red Rock rhyolite; intruded by granite	90—800
			Unconformity		
		Fault contact	Alder series	Shale and grit with some quartzite and conglomerate; locally metamorphosed; intruded by diorite porphyry, porphyritic pyroxenite, granite, and rhyolite porphyry	5000 ±
		Yavapai group (previously termed Yavapai schist)	Red Rock rhyolite	Massive rhyolitic flows and agglomerate with minor intrusives; intruded by granite	1000 ±
			Fault contact		
			Yaeger greenstone	Volcanic rocks of intermediate to mafic composition together with some intercalated sedimentary material; generally affected by low-grade metamorphism; intruded by diorite porphyry, granite, and rhyolite porphyry	2000 ±
				Base not exposed	

YAVAPAI GROUP

General statement.—The oldest rocks exposed in central Arizona consist of greenstone, rhyolite, shale, and grit, with some quartzite and conglomerate. In the Bradshaw Mountains and Jerome quadrangles, these rocks are somewhat schistose, depending upon local conditions of meta-

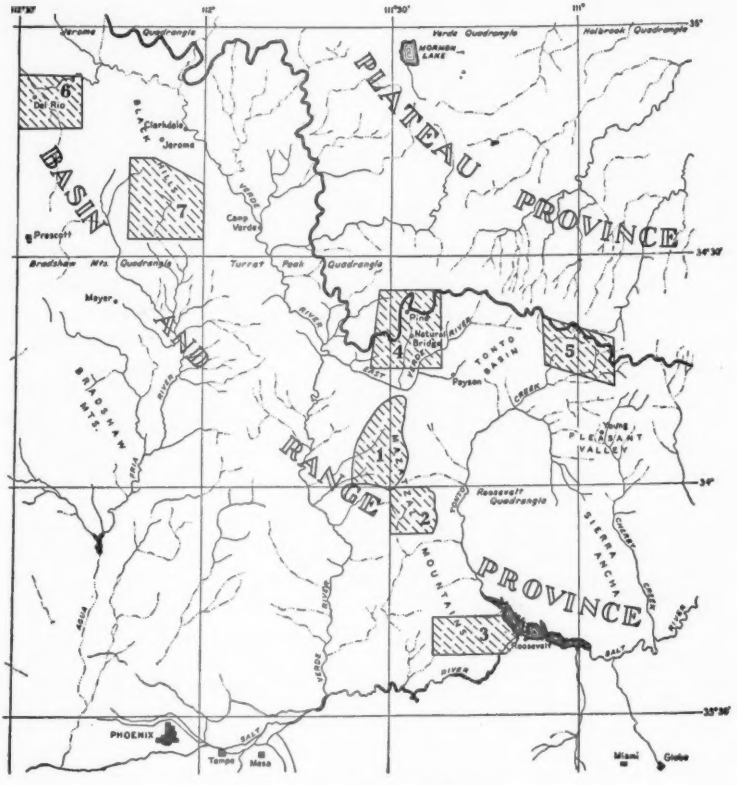


FIGURE 1.—*Index map of central Arizona*

Showing location of areas described in this report: (1) Northern portion of Mazatzal Mountains; (2) Central portion of Mazatzal Mountains; (3) Four Peaks; (4) Pine Creek; (5) Eastern Tonto Basin; (6) Del Rio; (7) Southern portion of Black Hills.

morphism, and were originally grouped together as one formation—the Yavapai schist (Jaggar and Palache, 1905; Lindgren, 1926). This usage was followed throughout the region in preparing the Geologic Map of Arizona. As the Yavapai formation is only locally schistose, however, it

is referred to in this paper as the Yavapai group rather than as the Yavapai schist. Its members are designated as the Yaeger greenstone, Red Rock rhyolite, and Alder series.

Yaeger greenstone.—Probably the oldest member of the Yavapai group is the greenstone that crops out in the Black Hills, Mazatzal Mountains, and eastern Tonto Basin areas. This member is here termed the Yaeger greenstone, from its typical occurrence east of the Yaeger mine, in the southwestern portion of the Black Hills.

The Yaeger greenstone characteristically forms ruggedly dissected slopes of 15 to 35 degrees, sparsely mantled by dark olive-drab soil and dense brush (Pl. 1, fig. 1). Like the oldest formation in the Lake Superior region, it is composed largely of intermediate to mafic flows and small intrusives, tuff, and agglomerate, together with some sedimentary material. These rocks show extensive alteration to greenish-black and grayish-green aggregates of fine-grained chlorite, sericite, and quartz, with local rude schistosity. They have undergone considerable deformation and were extensively invaded by pre-Cambrian batholithic masses of granite and small bodies of felsic to mafic composition. The thickness of the member has not been determined but appears to exceed 2000 feet.

The Yaeger greenstone is equivalent to the "greenstone complex" of the Black Hills, as described by Reber (1920; 1938), Lindgren (1926), Hansen (1930), and Lausen (1930), exclusive of the rhyolitic rocks, which, at least in part, are equivalent to the Red Rock rhyolite.

Red Rock rhyolite.—In fault contact with the Yaeger greenstone is a thick series of dominantly rhyolitic rocks, consisting of flows and minor amounts of agglomerate, breccia, and intrusives. This member, which crops out prominently in the Mazatzal Mountains, Pine Creek, eastern Tonto Basin, and southern Black Hills areas, is here termed the Red Rock rhyolite, from its typical occurrence in Red Rock Butte, in the central segment of the Mazatzal Range.

The Red Rock rhyolite tends to form blocky, joint-controlled slopes of 35 to 70 degrees or more, comparatively bare of soil and vegetation (Pl. 1, fig. 2). It is characteristically massive, with flow banding or bedding apparent only in places; its intrusive masses are not readily distinguishable from the flows. Owing to its massiveness and to deformation, the thickness of the rhyolite is unknown but apparently exceeds 1000 feet.

The typical rhyolite is a grayish-brown to reddish-brown dense rock that breaks with a splintery fracture whose surfaces reveal sparse small phenocrysts of quartz and orthoclase in a stony groundmass. Microscopically, the rock consists of a faintly banded, finely granular to microcrystalline groundmass of quartz and feldspar with locally corroded phe-

FIGURE 1. SLATY MEMBER OF ALDER SERIES
Alder Creek, Mazatzal Range.

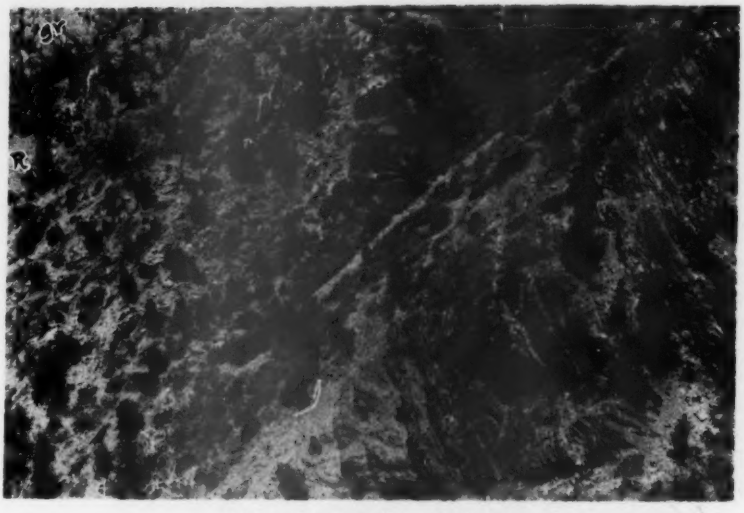


FIGURE 2. TILTED MAVERICK SHALE
Faulted against Red Rock rhyolite (R) which is intruded by pre-Cambrian granite (gr), Maverick Basin.

FORMATIONS AND STRUCTURE

FIGURE 1. MAZATZAL QUARTZITE CUT BY THRUST FAULT
Del Rio area.

FIGURE 2. CITY CREEK SERIES
With small-scale thrust in quartzitic member, north end of Mazatzal Range.

nocrysts of quartz and orthoclase generally less than 1.25 mm. in diameter.

In places the Red Rock rhyolite is porphyritic. In eastern Tonto Basin its phenocrysts commonly range up to 2.75 mm. in maximum dimension, and the rock locally contains numerous fragmental, fine-textured spherulites. Since, according to Grout (1932, p. 32, 232), spherulites form only in glass, this spherulitic rhyolite represents a devitrified glassy flow.

An exceptionally porphyritic variety occurs at the northern end of the Mazatzal Range and also below Natural Bridge, on Pine Creek. This variety is characterized by scattered phenocrysts, up to 5 mm. in diameter, of pink feldspar and sparse quartz in a dense groundmass. Examined microscopically, the feldspar phenocrysts are seen to consist of corroded orthoclase and minor albite which have undergone sericitization and, in places, complete kaolinization. The groundmass consists of microcrystalline, locally sericitized feldspar and quartz, extensively interspersed with finely divided hematite and irregular patches of chlorite.

During early reconnaissance work in the region (Ransome, 1916, p. 159; Wilson, 1922; Darton, 1925, p. 235, 249) this porphyritic rhyolite was loosely and erroneously classified as granite. Hinds (1935, p. 10) erred similarly in referring to the rhyolite at Natural Bridge as "Archean granite porphyry" and to conglomerate pebbles of this same rock as "granite" and "aplite."

The Red Rock rhyolite in places contains fragments of greenstone, which suggests that it is younger than the Yaeger greenstone.

Alder series.—In fault contact with the Yaeger greenstone and Red Rock rhyolite is a thick series of locally metamorphosed shale, grit, quartzite, and conglomerate. This division of the Yavapai group crops out extensively in the Mazatzal Mountains, eastern Tonto Basin, and Black Hills, and to a small extent in the Del Rio area. It is termed the Alder series, from its typical occurrence in the vicinity of Alder Creek, in the central segment of the Mazatzal Range.

The Alder series forms steep-sided canyons and sharp ridges, thinly mantled in places with soil and talus. Except for its massive quartzite and conglomerate beds, this series is characterized by thin lamination, generally parallel to original stratification. It is schistose in the vicinity of large intrusive bodies.

Shaly members, locally metamorphosed to slate (Pl. 2, fig. 1), phyllite, and schist, make up more than half of the Alder series. These members range in thickness from a few feet to apparently 4000 feet or more, but there is probably some duplication by faulting or folding. Aside from local differences in texture, these shaly rocks are prevailingly fine grained,

readily cleavable, and irregular to splintery on fractured surfaces. The most common variety consists largely of dark-gray to black locally arenaceous compact shale which cleaves into small slabs and flakes with smooth to splintery fracture. Another common variety is maroon to hematite red, locally spotted shale which breaks into smooth thin slabs several inches to more than a foot across. Microscopically, both varieties of shale consist of fine angular to ovoid grains of quartz, generally less than 0.1 mm. in diameter, in an abundant argillaceous cement of submicroscopic fineness. The maroon shale is rather hematitic, and the splintery variety carries numerous small shreds of kaolin. All of the mineral particles have their long dimensions parallel to the lamination. Schistose phases are characterized by alteration to finely divided muscovite, chlorite, and secondary calcite, and, in places, various contact silicates.

Approximately one-third of the Alder series is composed of dark-gray to brownish-gray argillaceous grit. This rock generally consists of poorly rounded to angular grains of quartz and feldspar, most of which are less than 2 mm. in diameter, in a finely divided muscovitic cement. Owing to stratification of the mineral particles, it is characteristically flaggy to thinly laminated, and some of its more micaceous beds resemble schist.

Conglomerate and quartzite, in many places grading into the grit, constitute about 15 per cent of the Alder series. The conglomerate members range in thickness from a few feet to 1000 feet and are generally lenticular. Depending upon the hardness of their cementing material, some form prominent reefs, whereas others have little distinctive topographic expression. This rock consists typically of subangular to rounded pebbles, most of which are less than 4 inches in diameter, of rhyolite, quartz, jasper, and quartzite in a gritty, argillaceous, locally micaceous cement. Microscopically, the rhyolite of the pebbles closely resembles the Red Rock rhyolite. The cementing material of the conglomerate is generally laminated, but the pebbles show little or no evidence of squeezing.

The quartzite members range from less than a foot to more than 150 feet in thickness and are characteristically lenticular. They are the most resistant of the Alder series and stand out as reefs, of which some are more than 50 feet high. Although prevailingly massive, they are in places thin bedded with shale partings. The rock is white to gray and grayish brown and generally cross-bedded. It ranges from fine grained to pebbly, in places grading into conglomerate and grit. It is commonly intersected by veinlets of white quartz.

The Alder series is equivalent to the sedimentary portion of the Yavapai schist. Owing to intense folding and faulting, the exposed thickness of the series is unknown; it appears, however, to exceed 5000 feet. As all the observed contacts of the Alder series with the Yaeger greenstone and Red

Rock rhyolite are faults, its relative age is not definitely known. The character of the rhyolite pebbles in its conglomerate members, however, strongly suggests that it is younger than the Red Rock rhyolite.

DEADMAN QUARTZITE

Resting upon an eroded, deeply oxidized surface of Red Rock rhyolite in the northern half of the Mazatzal Range, north of Latitude 34°, is the Deadman quartzite. This formation, named from its typical occurrence on the North Fork of Deadman Creek, consists of hard, fine- to medium-grained, thinly stratified, cross-bedded, cliff-forming quartzite, together with some thin conglomerate and hematitic shale members and an irregular basal conglomerate. In general, the upper third of the Deadman quartzite weathers grayish brown to white, in contrast with the reddish-brown tint of the lower portion. The thickness of the formation ranges from 90 to 110 feet except in a thrust block at the southeast where it attains approximately 800 feet (Pl. 5, fig. 1; Pl. 10). This thick segment may have been thrust to its present location from a place several miles farther southeast toward which the quartzite progressively thickened during deposition.

The basal conglomerate ranges from a few inches to 25 feet in thickness. It is made up largely of pebbles of rhyolite, quartz, and red jasper, a fraction of an inch to a foot in diameter, in a rusty-red argillaceous, sandy cement. Beneath the basal conglomerate the Red Rock rhyolite is extensively oxidized, in places to depths of more than 100 feet, indicating an erosion interval of considerable magnitude.

Found only within the northern half of the Mazatzal Range, the Deadman quartzite probably thins out northward, and to the south it has been removed by erosion. It does not crop out in contact with the Alder series, but, for reasons given later in this paper, it is believed to be younger.

MAVERICK SHALE

Overlying the Deadman quartzite with apparent conformity is the Maverick shale, named from its typical occurrence in Maverick Basin, in the northwestern portion of the Mazatzal Mountains.

In its type section the Maverick formation consists of thin-bedded, locally ripple marked, fine-grained, dense, gray shale generally sprinkled with fine flakes of mica on the bedding planes and containing alternating thin sandy to quartzitic beds in the upper portion. It has been recognized only within the Mazatzal Mountains. In the northern portion of the range, north of Latitude 34°, it lies with apparent conformity above the Deadman quartzite. Near the southern end of the range, on the western slope of Four Peaks, it has been intruded by granite at or near

the base. The Maverick shale is 800 feet thick at Maverick Basin but thins to about 500 feet at North Peak; apparently it thins greatly northward. Along the eastern flank of the range, it is generally deformed by drag folds which increase its apparent thickness (Pl. 6, fig. 1). On the western slope of Four Peaks, the formation measures approximately 1000 feet, but there, also, drag folding has thickened it.

In the vicinity of North Peak, the Maverick shale ranges from gray and dark gray to maroon with light-gray diffusion spots; the maroon color seems to be more common in the lower portion, which locally contains a few thin beds of gray quartzite. The base is characteristically ripple marked and micaceous. South of North Peak, the shale is prevailingly gray to pale greenish gray on fresh fracture, weathering to dull gray or pale yellowish.

In Barnhardt Canyon and on the western slopes of Mazatzal Peak, the interbedded quartzitic members of the upper portion are relatively abundant. Because of their massiveness and pale-brownish color, they contrast strongly with the shale and make its structure visible from a distance (Pl. 6, fig. 1). Microscopically, this interbedded quartzite consists of closely packed subangular to poorly rounded grains of quartz, up to 1.25 mm. in diameter, in a limonitic, finely granular quartz cement. Pronounced wavy extinction is characteristic of the quartz grains.

Of the exposure in Shake Tree Canyon, between Cactus Ridge and Mazatzal Peak, Ransome (1916, p. 158) says:

> "These shales resemble nothing I had previously seen in Arizona. They are gray-green, weathering yellow, fairly hard, and only moderately fissile. . . . For about 50 feet from their top they alternate with thin beds of quartzite and conglomerate. The conglomerate layers are less than a foot thick and carry pebbles of quartz and red jasper."

Microscopic examination of Maverick shale from several localities shows it to consist of fine quartz grains and micaceous shreds, well stratified in an ultra-fine, isotropic cement. The quartz grains are generally less than 0.10 mm. in diameter; the micaceous shreds are 0.15 mm. long, although exceptionally ranging up to 0.25 mm. in length. Some of this micaceous mineral is muscovite, but much of it is chlorite which imparts its greenish hue to the rock. Locally, the cement is marked by limonitic splotches.

According to the microscopic data, the Maverick shale is characteristically finer-grained and more argillaceous than the shale of the Alder series.

MAZATZAL QUARTZITE

General considerations.—The Mazatzal quartzite (Wilson, 1922, p. 304), named for the Mazatzal Range, crops out in four different areas

FIGURE 1. PRE-CAMBRIAN GRANITE, MAVERICK BASIN

FIGURE 2. FLAT-BANDED CARBONATE-JASPER DEPOSIT
Alder Creek, Mazatzal Range.

FORMATIONS

FIGURE 1. SYNCLINE IN THICK DEADMAN QUARTZITE
Cactus Ridge, Mazatzal Range.

FIGURE 2. FOLDED MAZATZAL QUARTZITE
Northwest of North Peak, Mazatzal Range.

in central Arizona. Resting with apparent conformity upon the Maverick shale and intruded in places by granite, it makes up the high, main ridge of the northern half, and the crest of Four Peaks at the southern end, of the Mazatzal Range. Along Pine Creek it lies unconformably upon the Red Rock rhyolite and is unconformably overlapped by Paleozoic and Tertiary beds. In northeastern Tonto Basin and in Christopher Mountain and vicinity, it occurs faulted against the Red Rock rhyolite and is unconformably overlapped by Apache, Paleozoic, and Tertiary formations. Near Del Rio it is in fault contact with metamorphosed shale of the Alder series and unconformably overlapped by Cambrian, Devonian, and Tertiary beds.

Typically, the Mazatzal quartzite is very hard, vitreous, fine to medium grained, prevailingly cross-bedded, and locally ripple marked. Its weathered surfaces are pale brown, reddish brown, light gray, or nearly white, but with a characteristic faint purplish tint that is particularly noticeable from a distance. Its strata, which prevailingly form rugged cliffs to boulder-controlled slopes (Pl. 8, fig. 2; Pl. 9, fig. 1) range from a few inches to several feet in thickness with 2- to 6-foot beds probably the most common. In places relatively thin members of conglomerate and maroon shale are present. On Pine Creek the formation has a basal conglomerate 300 feet thick.

Measured sections of the Mazatzal quartzite show it to be 1,300 feet thick in the Mazatzal Mountains, 3,800 feet on Pine Creek, and 1,780 feet near Del Rio.

Microscopically, the typical Mazatzal quartzite consists of a closely packed aggregate of angular to subangular quartz grains in a finely granular, siliceous, somewhat limonitic cement. The grains, most of which do not exceed 1 mm. in length, are characteristically 25 to 50 per cent longer than wide. The interbedded maroon shale of the formation consists of sparse, extremely small particles of quartz and kaolin in an abundant argillaceous, iron oxide cement. In places the shale is mottled, probably due to unequal diffusion of iron oxide.

Relation to the Yavapai group.—The Mazatzal quartzite, Maverick shale, and Deadman quartzite overlie only the Red Rock rhyolite. They have not been found above the Yaeger greenstone and Alder series, probably because the foundation provided by these folded, faulted, relatively soft members of the Yavapai group could poorly resist the erosion that the Red Rock rhyolite has withstood.

That the old rhyolite surface sloped southward is indicated by the presence and southward thickening of the Maverick shale and Deadman quartzite beneath the Mazatzal quartzite in the Mazatzal Mountains.

It is possible that the Mazatzal and Deadman quartzites were deposited as near-shore phases of the Alder series, although no direct evidence of such relation is apparent.

It also seems possible that, prior to deposition of the Deadman, Maverick, and Mazatzal strata, the region underwent uplift, accompanied by some faulting, and the areas of Red Rock rhyolite now overlain by these strata were stripped of any Alder rocks that may have covered them.

CITY CREEK SERIES

A thick series of shale beds with some interbedded quartzite is exposed at the northern base of the Mazatzal Mountains, on the western side of City Creek (Longitude 111°30′), beyond the northern limit of Plate 10. In this paper these beds are termed the City Creek series. This series crops out for an east-west length of about a mile in bluffs of a pediment overlooking the East Verde River and for approximately 1½ miles southward in the lower reaches of the tributary gulches.

The City Creek series comprises a faulted, somewhat folded block that appears to be a northward-plunging, spoon-shaped syncline with steepening limbs on the east and south. Its contacts with the Yaeger greenstone on the east, west, and south are greatly obscured by talus and brush but seem almost certainly to be steeply dipping faults. The series is intruded by a few narrow dikes of diorite porphyry and overlain with well-exposed, pronounced angular unconformity by Cambrian Tapeats sandstone.

Apparently the lowest exposed members of the series are at the southeastern margin of the pediment. There, the canyon of City Creek cuts through well-stratified grayish-black to purplish siliceous shale which is at least 800 feet thick and contains at the top a 15-foot member of alternating shale and novaculitic quartzite (Pl. 3, fig. 2). In places this black shale weathers splintery, not unlike a member of the Alder series south of Sheep Mountain. Microscopically, the black shale consists of angular particles of quartz and shreds of kaolin (?), stratified within an abundant pale-green, isotropic cement.

The next higher member of the series consists of thin-bedded, friable maroon shale, about 50 feet thick, with a 10-foot member of alternating novaculitic quartzite and shale at the top (Fig. 2).

Resting upon this member is thin-bedded maroon to purple shale with some interbedded quartzite. These beds, which dip rather steeply and extend northwestward beneath Paleozoic and Tertiary-Quaternary formations, have an apparent thickness of at least 1000 feet, but there is possibly some duplication by faulting or folding.

Farther northwest, where it reappears in the bluffs fronting the East Verde River, the City Creek series consists of very thin-bedded, friable grayish-green shale. As this member is very poorly exposed, its thickness and structure were not determined.

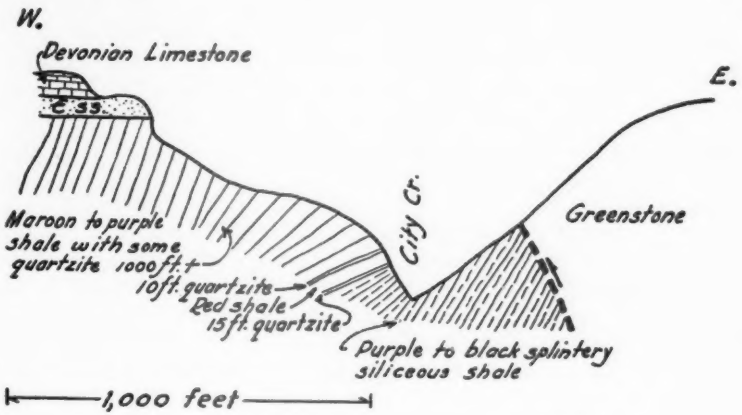


FIGURE 2.—*Sketch section across upper City Creek*

The relation of the City Creek series to the other pre-Cambrian rocks is unknown; it resembles nothing known in the pre-Cambrian of the Southwest and appears only in fault contact with the Yaeger greenstone. Affected by broad folds and small thrusts (Pl. 3, fig. 2), it probably antedates the great period of folding and faulting that involved the Mazatzal quartzite as described on subsequent pages. Possibly it represents the protected fault-block remnant of a succession, younger than the Mazatzal quartzite, that elsewhere has been removed by erosion.

DIORITE PORPHYRY

Dikes of grayish-black diorite porphyry are rather common in the Yaeger greenstone, Alder, and City Creek series. Most of these dikes strike northeastward, parallel to the regional lamination, indicating that they were intruded after the principal epoch of folding. As this folding affected the Mazatzal quartzite, they are probably younger than that formation. Most of them are too narrow for expression on the maps that accompany this paper.

Microscopically, the diorite porphyry consists essentially of extensively kaolinized feldspar, chloritized hornblende, and secondary quartz, together with some minor accessories. Its feldspar, where determinable, is chiefly oligoclase and some sodic labradorite. The rock bears a strong

field resemblance to the diorite porphyry (Jaggar and Palache, 1905, p. 5; Lindgren, 1926, p. 57-58) of the Bradshaw Mountains and Jerome quadrangles and may be essentially of the same age.

MT. ORD PYROXENITE

A stock of dense blackish porphyry, intruding the Alder series and in turn invaded by granite on its southeast, crops out as a belt three-quarters of a mile to 2⅛ miles wide that extends northeastward across the Mazatzal Range at Mt. Ord (Pl. 11). Many dikes of this rock, generally less than 75 feet wide and trending northeastward, intrude the Alder series for about 3000 feet from the stock.

Typical material from the stock is pale greenish gray on weathered surfaces and black on fresh fracture, with phenocrysts of pyroxene up to 5 mm. in diameter in a dense groundmass. Microscopically, the typical variety is seen to consist of well-formed phenocrysts of diopside (?) in a holocrystalline groundmass of finely felted pyroxene which in places has undergone considerable alteration to serpentine and chlorite. Near the granite the pyroxenite shows silicification of its groundmass.

An exceptional variety of the pyroxenite is characterized by small rounded segregations of the phenocrysts which, on weathered surfaces, stand out as nodules.

The relation of the Mt. Ord pyroxenite to the diorite porphyry has not been determined. Obviously guided by the northeastward-trending regional structure, the intrusion of the pyroxenite took place after the principal folding and faulting, which involved the Mazatzal quartzite.

GRANITE

Granite, intruding the Mazatzal quartzite and older rocks, makes up more than half of the Mazatzal Mountains and eastern Tonto Basin areas, the southern part of the Black Hills, and a small part of the Pine Creek area.

As a rule the granite forms steep, fairly rugged slopes, eroded under guidance of northwestward- and northeastward-trending joints (Pl. 4, fig. 1). In places, particularly west of Maverick Basin, it retains a fairly smooth surface, apparently the remnant of a pre-Cambrian peneplain.

This formation includes several varieties or phases that are believed to have been intruded from a common source during one general period.

The prevailing type of granite throughout the region is of medium to coarse texture and pinkish-brown color, deeply weathered to pale yellowish brown. Microscopically it consists of partially kaolinized feldspar, quartz, some chloritized biotite, and limonite derived from alteration of ferromagnesian minerals. Its feldspars are principally orthoclase and microcline, with some albite and microperthite.

FIGURE 1. DRAG FOLDS IN MAVERICK SHALE
Barnhardt Canyon, Mazatzal Range.

FIGURE 2. DRAG FOLDS IN LOWER BEDS OF MAZATZAL QUARTZITE, FADING OUT UPWARD
Barnhardt Canyon.

DRAG FOLDS

FIGURE 1. FOLDED DEADMAN QUARTZITE (D) AND RED ROCK RHYOLITE (R)
Thrust over Maverick shale (sh) which rests upon Deadman quartzite (D), 1¼ miles west of Mazatzal Peak.

FIGURE 2. RED ROCK RHYOLITE (R) IN REVERSE FAULT CONTACT WITH MAZATZAL QUARTZITE (M)
Haigler Creek.

FOLDS AND REVERSE FAULTS

In eastern Tonto Basin and the southern part of the Mazatzal Range, the granite is unconformably overlain by younger pre-Cambrian (Apache) beds. In the northern part of the Mazatzal Range, along the East Verde River, and in the Black Hills, it is unconformably overlain by Middle Cambrian sandstone. It is probably equivalent to the Bradshaw granite of the Bradshaw Mountains (Jaggar and Palache, 1905, p. 3-4) and the Ruin granite of the Globe district (Ransome, 1903, p. 74-75), with which it is virtually identical.

RHYOLITE PORPHYRY

Dikes of rhyolite porphyry occur sparsely in the Yaeger greenstone and Alder series at various places. These dikes generally do not exceed 50 feet in width, though the Pine Mountain dike which extends across the Mazatzal Range (Pl. 11) has a maximum width of a mile. Following the prevailing structure of the region, they strike generally northeastward to eastward. The locus of intrusion of the Pine Mountain dike was a fault contact between slate and conglomeratic grit.

The rhyolite porphyry is typically a fine-grained porphyritic gray rock that weathers pale yellowish gray. Microscopically, it shows phenocrysts of quartz, orthoclase, and sodic plagioclase in a microcrystalline groundmass of sericitized, kaolinized feldspar and quartz.

The smaller dikes of rhyolite porphyry show little or no dynamic metamorphism, but the Pine Mountain dike is laminated for some tens of feet inward from its edges. This lamination could be explained as a result of cooling of the dike and relief or readjustment of regional stresses, acting on original flow planes developed near the edges of the mass.

The concordance of the rhyolite porphyry dikes with the local and regional structure is strong evidence that they were intruded after the principal epoch of folding and faulting and hence are younger than the Mazatzal quartzite. They may be genetically related to the granite.

APACHE GROUP

The Apache group, consisting of a succession of quartzite, conglomerate, shale, and limestone (Table 1), unconformably overlaps the Yavapai group, Mazatzal quartzite, and granite in the eastern Tonto Basin area, and the granite at the southeastern end of the Mazatzal Range. It does not appear farther northwest in the central Arizona areas.

Ransome (1903, p. 28-39) originally classified the Apache group as Cambrian, but Darton (1925, p. 27-37) concluded that its portion below the Troy formation is younger pre-Cambrian. Later, Ransome (1932, p. 6) stated that

> "It has become increasingly probable during recent years that this restricted Apache group (below the Troy) is generally equivalent to the Unkar group (younger pre-Cambrian)."

Stoyanow (1936, p. 472-476) differentiated the Troy quartzite from the Apache group

> "not only because it overlaps the Mescal limestone, but because it carries Cambrian fossils and conformably underlies younger Middle Cambrian strata."

As now restricted, the Apache group includes only younger pre-Cambrian rocks.

The relative age of the Apache group is a most important factor from the standpoint of the present research. The establishment of its age as pre-Cambrian means that the granite, upon whose deeply eroded surface it unconformably rests, was intruded during a period of great crustal disturbance that obtained long before the end of pre-Cambrian time.

DIABASE

Diabase of uncertain age occurs as dikes and great sills intruding the Apache group. Ransome (1923, p. 10-11) found diabase cutting Paleozoic rocks in the Ray quadrangle and assigned it to the early Mesozoic or late Paleozoic. Short and Ettlinger (1926, p. 76) and Galbraith (1935) reached similar conclusions from studies in the Superior district. Darton, however, believes that the post-Troy diabase of Ray and Superior represents an intrusive younger than the great diabase bodies that elsewhere do not penetrate the Troy.

STRUCTURE OF CENTRAL ARIZONA REGION

GENERAL STATEMENT

The Older pre-Cambrian rocks of central Arizona have undergone intense folding, accompanied by reverse and normal faulting and widespread batholithic invasion, whereas the Younger pre-Cambrian, Paleozoic, and Tertiary formations have been dislocated mainly by normal faulting. The folds and reverse faults are of subparallel, northeastward to northward trend. Some of the normal faults strike parallel to these features, and others strike approximately at right angles to them.

The earlier folding, faulting, and associated igneous activity occurred long before deposition of the Apache group. Subsequently the region passed through many cycles of uplift, erosion, and subsidence but appears to have undergone comparatively little further deformation until normal faulting in late Tertiary time gave rise to the present mountain ranges.

FOLDS

The folds in central Arizona are of closed, open, and drag types. As a rule they plunge at low or moderate angles northeastward to northward, and their axial planes tend to dip southeastward. The formations involved in the folding are, in order of observed intensity, the Alder series,

Maverick shale, Deadman quartzite, Yaeger greenstone, City Creek series, Mazatzal quartzite, and Red Rock rhyolite, all of pre-Apache age.

The closed folds are sharp, steep-limbed flexures which tend to be slightly overturned northwestward. They range in width from a few inches to several thousand feet; the syncline exposed west of Mazatzal Peak (Pl. 10) has a minimum amplitude of 4000 feet, and the one indicated by Plate 11, in the central segment of the Mazatzal Range, appears to be more than 6 miles across. Throughout central Arizona most of the Alder series, a large part of the Yaeger greenstone, and in places the Red Rock rhyolite, Deadman quartzite, Maverick shale, and the lower portion of the Mazatzal quartzite are affected by folds of this type. The folded strata, particularly if argillaceous, are laminated parallel to original bedding, but, except on bends, show no change in thickness due to flowage and no microscopic evidence of recrystallization due to regional pressure. Their metamorphism to phyllite and schist is restricted to the vicinity of intrusive bodies, particularly of granite.

Open rather than closed folds predominate in the relatively competent Red Rock rhyolite, Deadman quartzite, and Mazatzal quartzite, and also in the City Creek series. These open folds are generally broad, gentle flexures whose limbs dip less than 50 degrees (Pl. 5, fig. 1), but some are sharp bends of which one limb, owing to northwestward overturning, dips steeply or is even vertical. They have the same northeastward to northward trend and plunge as the closed folds.

Drag folds, affecting all the deformed rocks, though best developed in the Maverick shale, Deadman quartzite, and the lower portion of the Mazatzal quartzite (Pl. 6), occur within the bends of many of the major folds and in the lower portions of the thrust slices. They are rather uniform, sharp flexures, generally less than 10 feet in amplitude, with pronounced northwestward overturn. Marking zones of differential movement, they die out or give way to bedding faults in the more competent rocks.

FAULTS

Age and expression.—The principal faults recognized in central Arizona are of two ages—pre-Apache and late Tertiary. The pre-Apache faults are of low-angle thrust and steeply dipping reverse and normal types that, as a rule, have not greatly influenced the present topography, whereas the Tertiary faults are of normal type and generally are expressed in the topography.

Reverse faults.—Striking parallel to the folds are numerous reverse faults which have greatly dislocated the Mazatzal quartzite and older formations but do not affect the Apache and younger rocks.

These reverse faults control some of the drainage lines and saddles. In places the actual fault plane is visible. Where hard, brittle rocks, particularly quartzite and rhyolite, are involved, the trace of the fault is marked by breccia and gouge, and the footwall is shattered.

The reverse faults dip from a few degrees to 80 degrees southeastward. The low-angle thrusts are apparent only in the more competent beds but possibly involve also the closely folded Alder series. Although some of the steeply dipping reverse faults probably followed the batholithic invasion, most of them appear to be related to low-angle thrusts. Because of insufficient key beds, their maximum displacement is generally indeterminate; in many cases it certainly exceeds 1000 feet.

The low-angle and steeply dipping reverse faults are particularly well exemplified by the Mazatzal thrust, a great low-angle initial shear fault that involves the northern half of the Mazatzal Mountains. From its apex in the saddle a mile south of North Peak, it is traceable southward for 7 miles, disappearing where intruded by pre-Cambrian granite on the southwest (Pl. 10) and concealed by Tertiary formations on the east, beyond the limits of Plate 10. It probably continues 10 miles farther southeastward, beneath the central segment of the range, to the intrusive bodies at Mt. Ord. Its displacement is at least 7 miles, and may exceed 17 miles. The exposed portion of the thrust cuts, with low southeastward dip, diagonally across the underlying gently southeastward dipping Mazatzal strata. Above the fault are imbricated, slightly deformed to closely folded sheets of Red Rock rhyolite, Deadman quartzite (Pl. 7, fig. 1), Maverick shale, and Mazatzal quartzite. These sheets are separated by steeply southeastward dipping reverse faults which branch upward from the sole. Above the presumed southeastward extension of the thrust in the central segment of the range are blocks of Red Rock rhyolite and folded, steeply tilted Alder beds. These blocks are separated by steeply dipping faults (Pl. 11) that strike northeastward.

Tear faults.—The pre-Apache rocks are cut in places by vertical faults which strike northwestward, perpendicular to the folds, and affect the topography only because they are zones of weakness to erosion. They are further characterized by horizontal displacements of a few hundred feet, but their vertical displacements are generally indeterminate. A fault of this type exposed along the South Fork of Deadman Creek, in the Mazatzal Mountains (Pl. 10), shows a displacement of approximately 150 feet vertically and more than 200 feet horizontally. Another, between Red Rock and Sheep Mountain, in the same range (Pl. 11), has a displacement of approximately 300 feet horizontally and an unknown amount vertically.

FIGURE 1. UPTURNED DEADMAN QUARTZITE
Cactus Ridge syncline, Mazatzal Range.

FIGURE 2. UPTURNED MAZATZAL QUARTZITE
Pine Creek area.

STRUCTURE

FIGURE 1. DEFORMED MAZATZAL QUARTZITE OF FOUR PEAKS ROOF PENDANT
Bluffs are 1000 feet high.

FIGURE 2. CONTORTED MAVERICK SHALE
Intruded by aplitic dikes, Four Peaks.

STRUCTURE

These faults are interpreted as pre-Apache tears which resulted from the compressive stresses that gave rise to the folds.

Normal faults.—Normal faults are fairly abundant in central Arizona. Part of them, truncated by a pre-Cambrian erosion surface and overlain by undisturbed Cambrian strata, are of pre-Cambrian—probably pre-Apache—age. Some are of indeterminate age, but, wherever they lack topographic expression they may reasonably be regarded as pre-Cambrian. Others are strongly reflected in the present topography and in places cut Tertiary beds.

The normal faults of known and supposed pre-Cambrian age strike northeastward to northward, dip steeply, and show displacements of a few tens to several thousand feet. They are well exemplified in the northern and central portions of the Mazatzal Range (Pls. 10 and 11) and in the Black Hills (Fig. 10).

The later normal faults of Tertiary age make up two main systems of which one strikes northwestward to westward and the other northeastward to northward. Their displacement ranges from a few feet to more than 1000 feet. They dip steeply or even vertically and are characterized by strong reflection in the present topography. Minor faults of this type occur locally within the mountains, as shown in the Pine Creek area. Those of great displacement are found in places separating the Tertiary (Pliocene) beds of the valley troughs from the hard rocks of the mountain ranges. There appears to have been little or no tilting associated with these faults north of Latitude 33°45′. No true fault scarps are present, but the mountain fronts may be regarded as profoundly eroded fault-line scarps. The mountain ranges stand above the intervening valley troughs because the upthrown mountain blocks have been more resistant to the erosion of Quaternary time than have the soft Tertiary beds of the downthrown blocks.

CORRELATION OF STRUCTURAL FEATURES

The volcanic activity that formed the earliest known rocks—the Yeager greenstone and Red Rock rhyolite—was doubtless occasioned by crustal unrest, but its associated structural features are obscure. It was followed by a long period of erosion and sedimentation during which the several thousand feet of Alder beds was deposited. This sedimentation was interrupted by regional uplift, accompanied probably by faulting and consequent denudation of large areas of Red Rock rhyolite upon which the Deadman quartzite, Maverick shale, and Mazatzal quartzite unconformably rest. Hence some of the normal faults that separate Yeager greenstone and Red Rock rhyolite from Alder beds possibly originated in pre-Mazatzal time. No pre-Mazatzal granite is recognized.

The field relations indicate that the major features of pre-Cambrian structure in central Arizona resulted from one profound crustal disturbance, termed the Mazatzal Revolution, which occurred after deposition of the Mazatzal quartzite and long before Apache sedimentation. The subparallel folds, thrust faults, and imbricate, steeply dipping reverse faults, so strongly developed in the Mazatzal quartzite and older formations, clearly resulted from intense northwestward-southeastward regional compression; the overturn of the folds indicates that the direction of thrusting was northwestward. The tear faults, which strike normal to the trend of the folds, are believed to have been formed by shearing stresses set up by the compression. Widespread igneous activity, consisting of the intrusion of dioritic to pyroxenitic stocks and dikes and the largest batholithic invasion of granite in central Arizona, culminated this most intense crustal disturbance. The intrusive bodies show a marked parallelism with the regional structure. The regional compression caused lamination and slaty cleavage but no marked recrystallization in the incompetent rocks; schistosity is apparent only in the vicinity of the larger intrusive bodies. Readjustments consequent upon the compression and igneous activity gave rise to normal and steeply dipping reverse faults of northeastward strike.

The Tertiary block faults, which are parallel to pre-Apache structural features, probably followed breaks or zones of weakness inherited from the Mazatzal Revolution.

MAZATZAL MOUNTAINS

INTRODUCTION

The Mazatzal Mountains are in central Arizona, near the southwestern margin of the Plateau (Fig. 1). The range trends about N. 30° W., from the Salt River on the south to the East Verde River on the north, between the valley of Tonto Creek on the east and the Verde River on the west. It is 50 miles long by 12 to 18 miles wide and has a somewhat sinuous crest that presents a skyline of prevailingly rounded, though locally rugged, peaks and saddles. Mazatzal Peak, the highest point in the range, is approximately 7900 feet above sea level and 6000 feet above Salt River. Most of the range is asymmetrical in cross section, with the slopes considerably shorter and steeper on the east than on the west. The slopes on both sides have been intricately dissected by deep and narrow canyons.

The topography of the range, as mapped by the United States Geological Survey, is shown on the Roosevelt and Turret Peak sheets (Scale 1 : 125,000) and the Payson advance sheet (Scale 1 : 48,000). Unfortunately, the Payson sheet, which includes the eastern slope of the north-

ern third of the range, was not completed before the field work for this paper.

The highway from Roosevelt to Payson follows the valley of Tonto Creek and connects with the Bush Highway, which skirts the southwestern portion of the range and crosses its middle segment. A few branch roads lead to mines and prospects. The northern foot of the range is reached by a road from Payson to Taylor's ranch, on the East Verde River. A few trails cross the mountains, but much of the country is so rugged and brushy as to be accessible only on foot, and many of the brushy areas cannot be penetrated without cutting.

In 1912 Ransome (1916, p. 157-166) made two short trips into the eastern portion of the Mazatzal Mountains incidental to a general study of Paleozoic sedimentation in Arizona. He described a pre-Cambrian rhyolite, unconformably overlain by a series of quartzite and shale whose structural relations were not understood. He inferred that these rocks had constituted a barrier ridge in the Paleozoic seas.

In 1914 Ransome (1915, p. 111-128) examined the quicksilver deposits in the central part of the range and gave a tentative interpretation of the local structural features.

The mapping of the range for the Geologic Map of Arizona was limited to a broad classification of the formations (Wilson, 1922, p. 299-312), with no attempt to work out the structural details.

In 1924-1926, Lausen (1927, p. 60-105; 1926, p. 782-791) and Gardner made a brief study of the quicksilver resources.

The present investigation of the Mazatzal Mountains occupied approximately 4 months' time, distributed over widely separated intervals from the middle of 1930 until late 1935. The geology is represented on Plates 10, 11, and 12.

YAVAPAI GROUP

The Yaeger greenstone, Red Rock rhyolite, and Alder series, which constitute the Yavapai group and were previously lumped together as the Yavapai schist, appear extensively in the Mazatzal Mountains, north of Mt. Ord.

Greenstone occurs throughout several square miles in the northernmost portion of the range (Pl. 10). Small areas of so-called "greenstone" occur within the Alder series but they are chloritized or dark ferruginous beds of that series rather than of the Yaeger.

The greenstone of the Mazatzal Mountains is intruded by the post-Mazatzal—pre-Apache granite on the south and by a small stock of similar granite at the eastern base of North Peak, beyond the limits of Plate 10. It is overlain by a few remnants of Middle Cambrian Tapeats sandstone (Pl. 1, fig. 1), Devonian limestone, and Tertiary rocks

but is in fault contact with the other formations of the area. Its pre-Cambrian age is established by field relations with Paleozoic beds and with the post-Mazatzal—pre-Apache granite. Composed largely of intermediate to basic volcanic rocks that have been extensively affected by low-grade metamorphism, the greenstone of this range constitutes a readily distinguishable unit that closely resembles the Yaeger greenstone of the Black Hills.

The Red Rock rhyolite which, for reasons already indicated, is regarded as next younger than the Yaeger greenstone, has been faulted against the greenstone on the north, intruded by the post-Mazatzal granite on the west, and unconformably overlain by Deadman quartzite. It is the basement rock from North Peak to Cactus Point. From Cactus Point to a fault contact with the Alder series at the southern base of Sheep Mountain (Latitude 34°), it forms the high main ridge. In its type locality of Red Rock, a butte in the central segment of the range (Pl. 11), the rhyolite is limited on the northwest and southeast by fault contact with Alder beds.

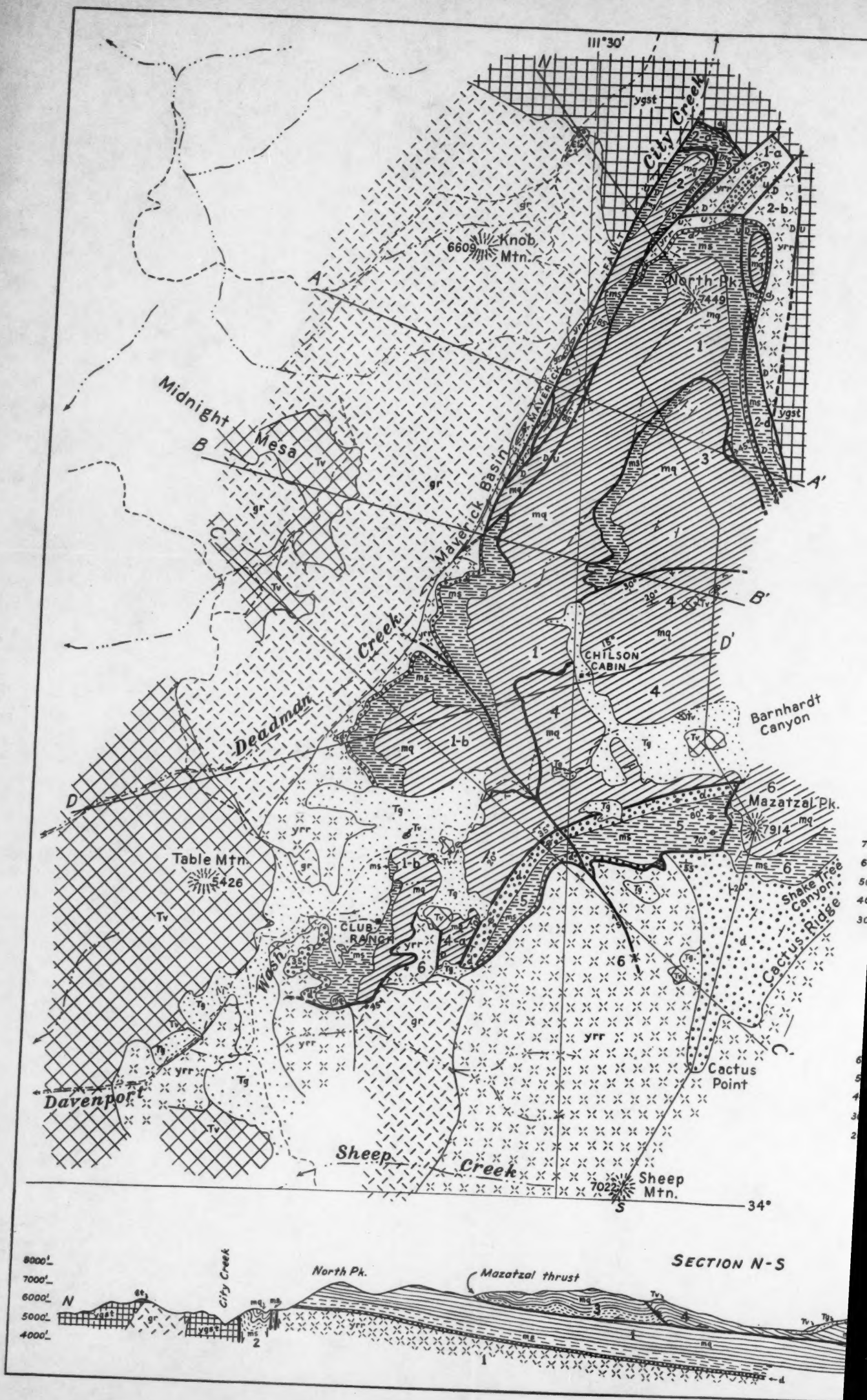
The Alder series, which is regarded as next younger than the Red Rock rhyolite, occurs typically in the basin of Alder and Slate creeks, in the central segment of the range (Pl. 11). Between Sheep Mountain and Mt. Ord the series crops out as two northeastward-trending belts separated by the fault block of Red Rock rhyolite that includes Red Rock. On the northwest the northern belt is in fault contact with the Red Rock rhyolite of Sheep Mountain, and the southern belt terminates on the south at the Mt. Ord pyroxenite intrusion. Fair to excellent exposures on some of the slopes and in many of the canyons reveal the succession generalized on Plate 11.

DEADMAN QUARTZITE, MAVERICK SHALE, AND MAZATZAL QUARTZITE

In the northern portion of the Mazatzal Mountains the Red Rock rhyolite is unconformably overlain by the Deadman quartzite, succeeded by the Maverick shale and Mazatzal quartzite; these strata make up the high main ridge from North Peak to Cactus Point. Their general features have already been described.

As indicated at the head of Maverick Basin, the Deadman, Maverick, and Mazatzal formations were probably intruded by the pre-Cambrian granite in the northwestern part of the area. They do not appear in the central segment of the range. In the southern portion, at Four Peaks, the Maverick shale and Mazatzal quartzite (Pls. 9, 12) occur as a roof pendant of the pre-Cambrian granite batholith, but the Deadman quartzite is not exposed.

Above the Mazatzal thrust (Pl. 10), the Deadman, Maverick, and


111°30'
N
City Creek
ygst
1-a
2
2-b
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Knob
6609
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1
3
Midnight
Mesa
A
A'
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C
C'
D
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Maverick Basin
Maverick
Creek
Deadman
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4
4-a
5
6
CHILSON
CABIN
Barnhardt
Canyon
Mazatzal Pk.
7914
Table Mtn.
5426
CLUB
RANCH
Wash
Shake Tree
Canyon
Cactus Ridge
Cactus
Point
Davenport
Sheep
Creek
Sheep
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7022
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34°
SECTION N-S
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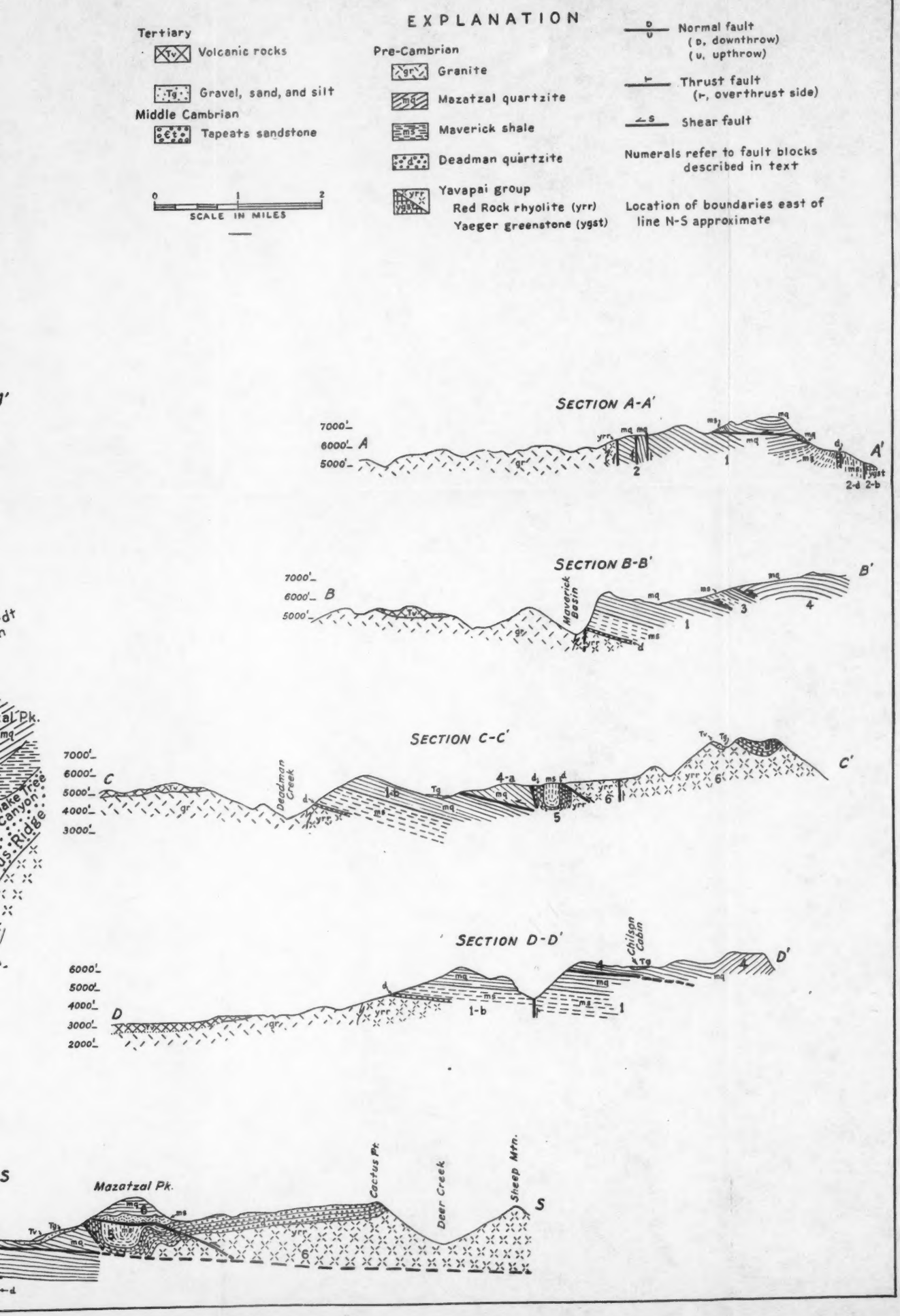
5000'
4000'
N
City Creek
North Pk.
Mazatzal thrust
S



THERN PORTION OF MAZATZAL MOUNTAINS

Mazatzal formations have been extensively dislocated by folding and faulting, but beneath it their sequence remains undisturbed. Their most complete succession appears on the eastern side of Maverick Basin (North Fork of Deadman Creek, near B-B′, Pl. 10). Here the canyon wall slopes from an altitude of 6500 to 3900 feet in half a mile and affords the following section:

Section on eastern wall of Maverick Basin

	Thickness in feet
Mazatzal quartzite	
Top of spur; altitude 6500 feet	
(1) Quartzite, hard, vitreous, fine-grained, cross-bedded; beds a foot or less thick and ripple-marked	250
(2) Quartzite, hard, vitreous, fine-grained, cross-bedded; beds 2 feet or more thick	225
(3) Quartzite like (2) but coarser and less vitreous	75
(4) Quartzite, hard, medium- to coarse-grained, prevailingly cross-bedded; grayish-brown, weathering brownish; beds mostly 2-6 feet thick and cliff-forming	300
(5) Quartzite similar to (4) but fine- to medium-grained, more vitreous, and locally cross-bedded; some beds weather hackly	210
(6) Quartzite, hard, fine-grained, brownish-gray, weathering dark brown; beds 2 feet thick near top, grading to less than a foot thick in lower portion	240
Total Mazatzal quartzite	1300
Maverick shale	
(7) Shale, thin-bedded, fine-grained, dense, gray; locally ripple marked and micaceous on bedding planes; contains alternating sandy to quarzitic beds in upper few feet	800
Deadman quartzite	
(8) Quartzite, hard, fine-grained, cross-bedded, weathers reddish brown; beds six inches to a foot thick; forms bluff	75
(9) Quartzite, hard, fine-grained to pebbly, thin-bedded. Bedding planes marked by thin layers of maroon shale containing small flakes of muscovite; weathers light gray and forms bluff	15
(10) Conglomerate of small rounded pebbles of rhyolite and quartz in a siliceous cement	½–2
Total Deadman quartzite	92
Red Rock rhyolite, upper portion somewhat oxidized.	

CITY CREEK SERIES

The City Creek series, which occurs at the northern base of the range, has already been described in this paper.

DIORITE PORPHYRY AND MT. ORD PYROXENITE

Dikes of diorite porphyry intrude the Yaeger greenstone, Alder, and City Creek series. The Mt. Ord pyroxenite intrudes the Alder series. The character and occurrence of these intrusives has already been described.

GRANITE

Granite constitutes more than half of the Mazatzal Mountains area. In the northern portion of the range it crops out over a large area west

of the main ridge and as a small area southeast of North Peak, beyond the eastern limit of Plate 10. In the southern part of the area it forms the bulk of the range from Mt. Ord to the Salt River.

This formation includes several varieties or phases whose detailed study and separation are beyond the scope of the present problem. They appear, however, to have been intruded from a common source during one general period at the culmination of the Mazatzal Revolution.

On the western side of the range, north of Latitude 34°, the granite is unconformably overlain by Paleozoic and Tertiary beds. It intrudes Yaeger greenstone on the north and Red Rock rhyolite on the southeast. Its contact with the Red Rock rhyolite is well exposed in Maverick Basin where the granite has a fine-grained border phase "frozen" to the rhyolite and contains inclusions of rhyolite up to 10 by 6 feet in size. Near the head of this basin a tongue of the granite 300 feet wide intrudes the rhyolite. About half a mile farther north a similar tongue of granite intruding the rhyolite is separated from the Mazatzal quartzite by only a few hundred feet of talus. The quartzite here is extensively silicified and veined with quartz stringers which in the Maverick fault zone form a prominent quartz lode that is traceable for about 7 miles farther southwestward. This southeastern contact of the granite, along the North Fork of Deadman Creek, forms a rather straight line and appears to have been localized by the Maverick fault.

The granite of the small stock that intruded the Yaeger greenstone southeast of North Peak, beyond the eastern limit of Plate 10, is similar to the granite of the northwestern part of the range.

Finer-grained phases, weathering pinkish or pale reddish brown, are locally common, as in the vicinity of the Mazatzal trail east of Knob Mountain.

Granite intrudes the Mt. Ord pyroxenite on the southeastern slopes of Mt. Ord and forms most of the range from there to the Salt River. In general, this granite is of similar appearance and identical mineralogic composition to the granite of the northwestern part of the area. Southward it is predominantly of coarser texture, with orthoclase phenocrysts ranging up to 2 inches in diameter. Aplitic phases occur prominently in the area northeast of Four Peak Pass.

The granite mass of the southern part of the area has a roof pendant of Maverick shale and Mazatzal quartzite at Four Peaks (Pl. 12) and includes numerous, mostly small masses of schistose, altered rock, particularly in the area extending for 3½ miles east of Four Peaks. Here are notable areas of medium-grained hornblende diorite which appear to be border phases of the granite, although they may represent a separate intrusion. Five miles east of Four Peaks the granite unconformably

underlies Apache strata. Microscopic examination shows that this pre-Apache granite is mineralogically identical to the granite of the northwestern part of the range.

PINE MOUNTAIN PORPHYRY

The Pine Mountain porphyry, which occurs sparsely as dikes at various places in the Yaeger greenstone and Alder series, is prominent only in the vicinity of Pine Mountain, in the central part of the range (Pl. 11). This rock has already been described.

APACHE GROUP

In the southeastern portion of the Mazatzal Mountains, in the vicinity of Roosevelt Dam, Apache strata unconformably overlie the pre-Cambrian granite (Pl. 12) and underlie Middle Cambrian Troy sandstone.

Ransome (1916, p. 149-152) measured the following section of the Apache beds in the canyon of Salt River at Roosevelt Dam:

Apache group

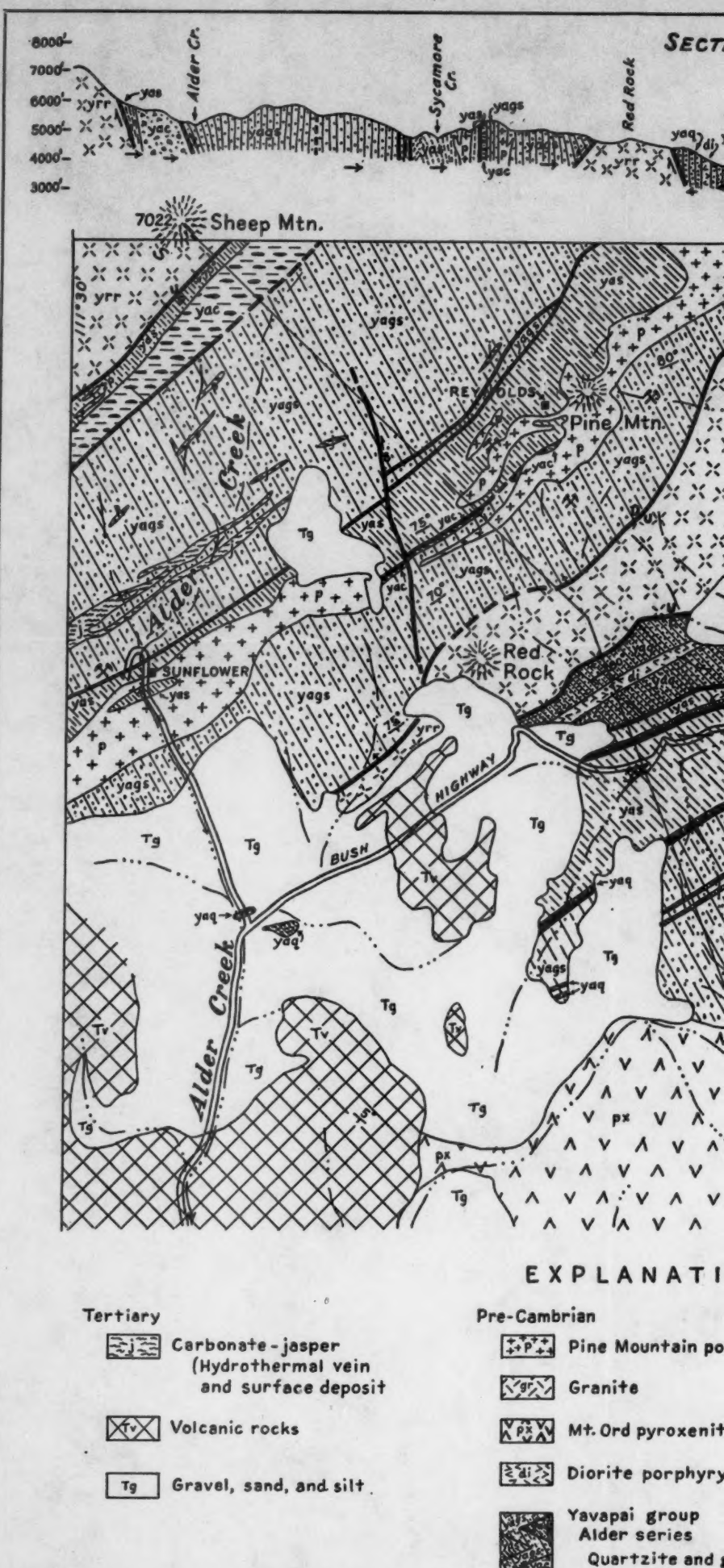
	Thickness in feet
(1) Vesicular basalt flow	50
(2) Mescal limestone: Hard, rather thin-bedded cherty dolomitic limestone	300
(3) Dripping Spring quartzite: Fine-grained vari-colored arkosic quartzite, much of it with dark-red and gray banding; partings between beds not distinct; ripple-marked	500
(4) Barnes conglomerate: Pebbles mainly of white quartz and hard vitreous quartzite generally less than 4 inches in diameter, in abundant sandy matrix	20
(5) Pioneer shale: Maroon shale grading into hard arkosic sandstone below. Intruded by diabase sill probably 800 feet thick	255
(6) Scanlan conglomerate: Well-rounded pebbles, up to 9 inches in diameter, of white quartz, brown fine-grained vitreous quartzite, and a little red jasper, closely packed in a matrix of dull red-brown coarse sandstone. Rests upon coarse-grained reddish granite	30
Total	1155

The quartzite pebbles of the Scanlan and Barnes conglomerates are lithologically identical to the Mazatzal quartzite. Probably they were derived from some nearby portion of the ancient Mazatzal Mountain range; in this locality their large size indicates that they did not travel far.

As previously stated, the Apache section below the Troy quartzite or sandstone is regarded as Younger pre-Cambrian. It is separated in age from the Mazatzal quartzite by an interval that included the Mazatzal Revolution and extensive peneplanation.

CARBONATE-JASPER DEPOSIT

Extending northeastward across lower Alder Creek, southwest of Pine Mountain, is a zone about an eighth of a mile in maximum width of yellowish dolomitic limestone with red jasper (Pl. 11). It occurs as



GEOLOGIC MAP OF CENTRAL PART OF

NATION

- ntain porphyry
- yroxenite
- orphyry
- group
- eries
- ite and grit (yaq)
- (yas)
- hale, and slate (yags)
- merate (yac)
- k rhyolite (yrr)

D / U — Normal fault (D, downthrow) (U, upthrow)

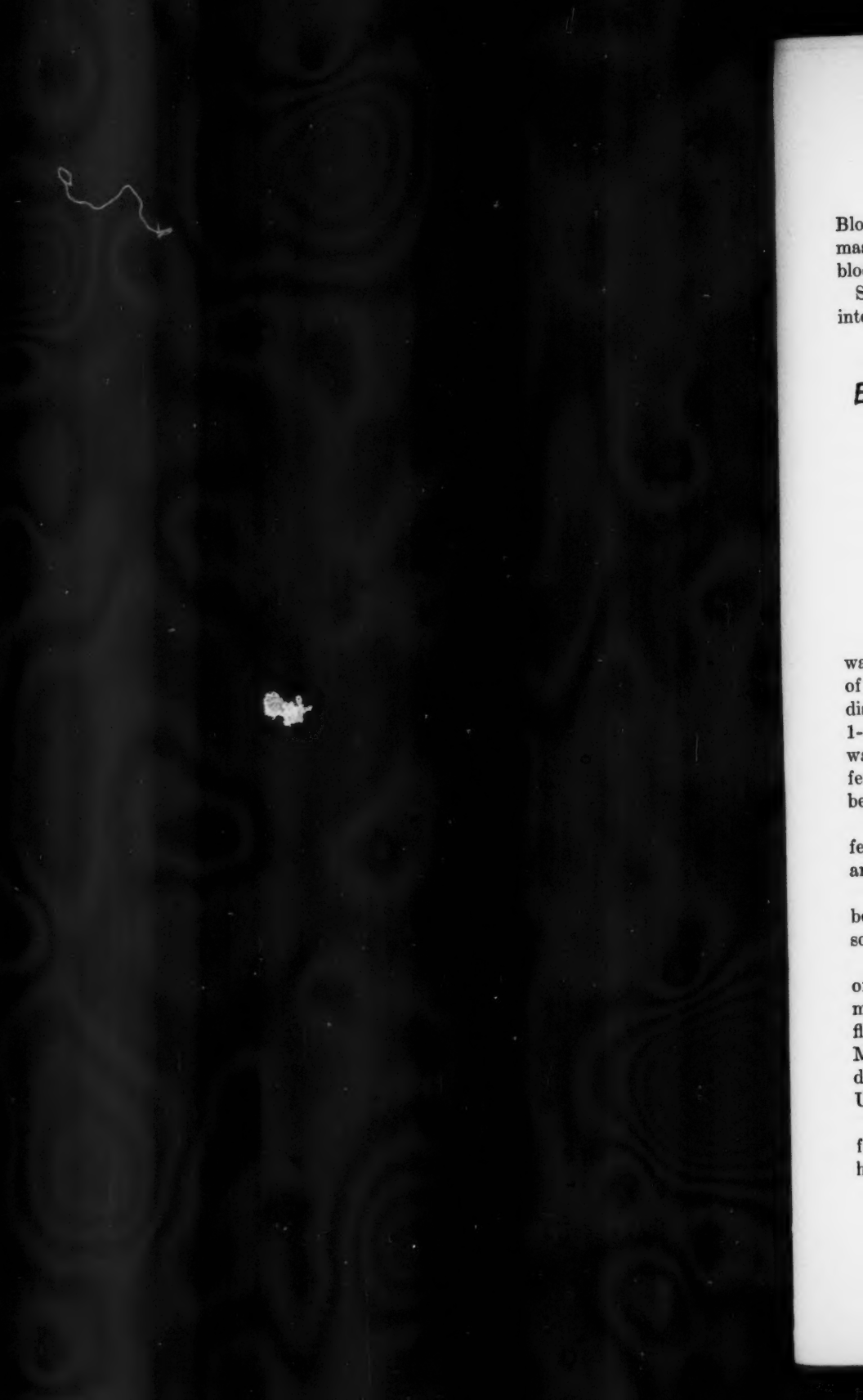
Thrust fault (⊢, overthrust side)

Shear fault

Direction of movement on faults in section

Top side of beds in section

ART OF MAZATZAL MOUNTAINS



Blocks 2, 2-a, 2-b, 2-c, and 2-d are interpreted as portions of the thrust mass, which have been dislocated by normal faulting in reference to block 1.

Southwest of North Peak the beds of blocks 1 and 1-b are gently flexed into a broad open syncline of low southwestward pitch. This southwest-

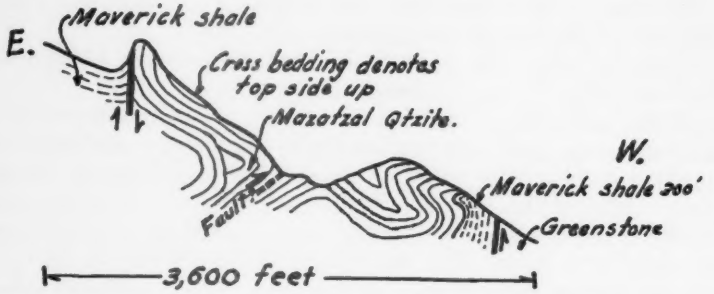


FIGURE 3.—*Sketch section of folds northwest of North Peak*

ward pitch is in marked contrast to the prevailing northeastward pitch of the folds in the thrust masses. Southwest of the Club Ranch, block 1-b displays a broad, open anticline of northeastward pitch. Blocks 1 and 1-b are separated at the South Fork of Deadman Creek by a northwestward-trending tear fault that shows a displacement of approximately 150 feet vertically and more than 200 feet horizontally. Block 1 is a horst between blocks 2 and 2-d.

Block 1-a has been dropped by normal faulting for approximately 100 feet in reference to block 1. It is an untilted horst between blocks 2 and 2-a on the northwest and 2-b on the southeast.

Blocks 2 and 2-a are complex thrust slices which occur as a graben between Yaeger greenstone on the northwest and blocks 1 and 1-a on the southeast.

In block 2-a is exposed a faulted syncline that trends somewhat west of north. This radical departure from the trend of the regional folding may have been caused by some pre-existing, opposing structure that deflected the compressive forces. A similar explanation was suggested by Mansfield (1927, p. 383) to explain the almost right-angle change in direction of the Rocky Mountain thrusts along the northern base of the Uinta Mountains.

The northeastern fourth of block 2 has undergone intense folding and faulting, as shown by Figure 2 of Plate 5 and by Figure 3. This block has been depressed about 500 feet in reference to block 1-a, and its

southwestern portion is intruded by the pre-Cambrian granite on the northwest (Pl. 2, fig. 2). Its contact with the granite appears to have been localized by a southwestward continuation of the fault that separates it from the Yaeger greenstone on the northwest. In Maverick Basin, this fault formed a zone, two branches of which are shown on Plate 10. It is termed the Maverick fault zone.

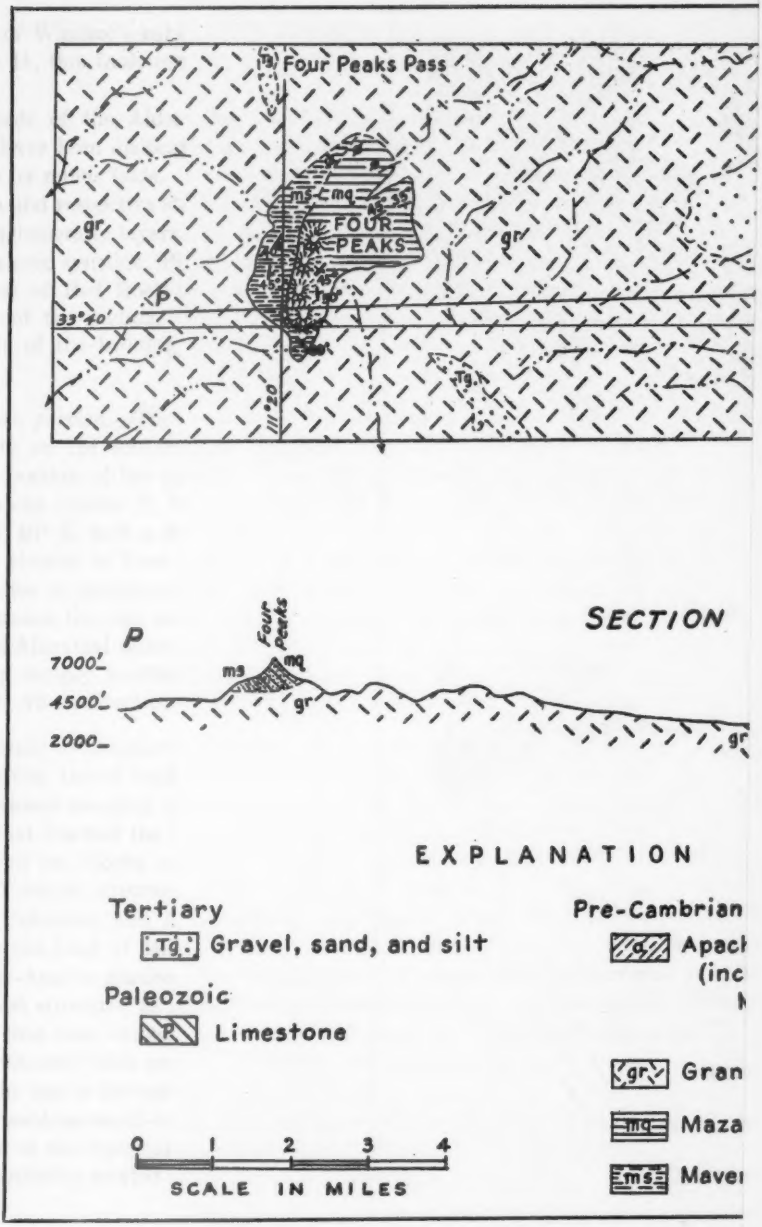
Northeast of North Peak, block 2-b is overlain by a small thrust slice (2-c) of contorted Mazatzal quartzite.

Block 4-a, thrust upon block 1-b, is separated from block 4 by the tear fault in the South Fork of Deadman Creek.

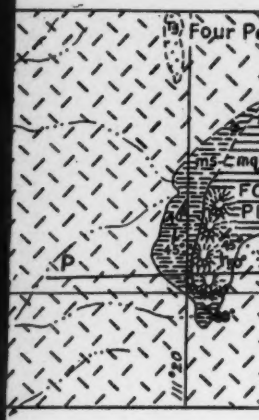
Block 5 is separated from blocks 4 and 4-a by a steeply southeastward-dipping reverse fault. Its beds are folded into a gently northeastward-pitching closed syncline whose southeastern limb passes sharply into the broad anticline (Pl. 10) that underlies block 6; these folds are overturned northwestward. The Deadman quartzite in block 5, which is seven or eight times thicker than the normal, may have been thrust to its present location from a place several miles farther southeast toward which it progressively thickened during deposition.

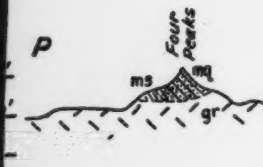
Block 6, which includes Mazatzal Peak, Cactus Ridge, and Sheep Mountain, is a large thrust slice overlying blocks 5 and 1-b. Its Deadman quartzite, like that of block 5, is 700 to 800 feet thick. Southeast of the Club Ranch the Red Rock rhyolite of this block is intruded by the pre-Cambrian granite. South of this ranch the rhyolite is separated from the granite by a steeply southeastward dipping reverse fault (Pl. 10) that is interpreted as having followed closely upon the intrusion. The strata of block 6 have been strongly affected by drag folds whose overturning indicates that the thrusting was northwestward. South and southeast of Mazatzal Peak is a broad, open, northeastward-pitching syncline, overturned northwestward. Its eroded, steeply dipping southeastern limb forms Cactus Ridge (Pl. 8, fig. 1) and Cactus Point (Pl. 5, fig. 1; Pl. 10). As exposed on the North Fork of Deer Creek (Shake Tree Canyon), near the eastern base of the mountains and beyond the limits of Plate 10, the Deadman beds show a slight discordance in dip that Ransome (1916, p. 158, fig. 13) attributed to a sharp anticline. Detailed examination, however, reveals good tangential cross-bedding that proves that the top side of the beds throughout this section is toward the northwest.

Central portion.—The Mazatzal thrust probably dips deeply beneath the middle segment of the range. Block 6 terminates at the southeastern base of Sheep Mountain (Pl. 11) where a fault that strikes northeastward and dips 70° SE. separates it from red shale of the Alder series. In the



GEOLOGIC MAP OF FOUR PEAKS AREA, MAZATZA





Tertiary

Tg Gravel, sand

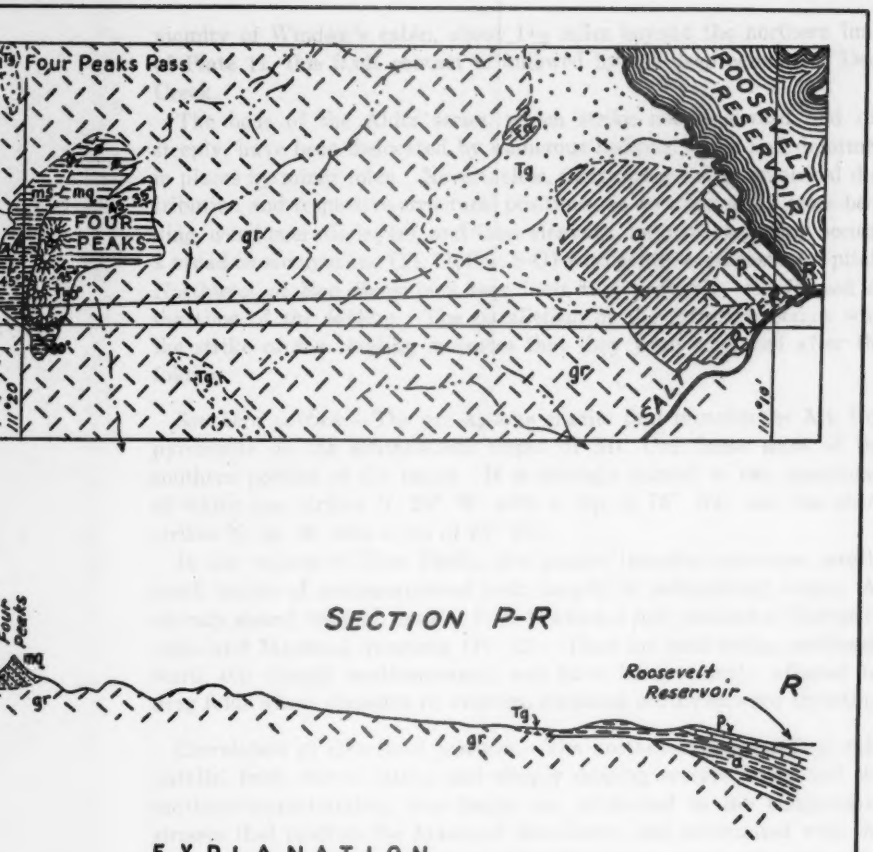
Paleozoic

P Limestone

0 1 2

SCALE IN MI

GEOLOGIC MA



OGIC MAP OF FOUR PEAKS AREA, MAZATZAL MOUNTAINS

vicinity of Windsor's cabin, about 1½ miles beyond the northern limit of Plate 11, this fault contact is followed by the deep canyon of Deer Creek.

The beds of the Alder series, which strike northeastward and dip steeply, have been dislocated by numerous bedding faults and deformed in places by minor folds. Nevertheless, their somewhat symmetrical distribution and respective structural positions, as determined by cross-bedding, conglomeratic layers, and false cleavage, indicate that they occupy a broad closed syncline (Pl. 11, Sec. S-O) with gentle northeastward pitch. Northwest of Red Rock is a tear fault that probably was formed at the time of the folding. The parallelism of the intrusive bodies with the strike of the bedding indicates that they were emplaced after the folding.

Southern portion.—The pre-Apache granite that intrudes the Mt. Ord pyroxenite on the southeastern slopes of Mt. Ord forms most of the southern portion of the range. It is strongly jointed in two directions, of which one strikes N. 25° W. with a dip of 75° NE. and the other strikes N. 40° E. with a dip of 75° SE.

In the vicinity of Four Peaks, this granite includes numerous, mostly small bodies of metamorphosed rock, largely of sedimentary origin. As already stated, the high mass of Four Peaks is a roof pendant of Maverick shale and Mazatzal quartzite (Pl. 12). Here the beds strike northeastward, dip steeply southeastward, and have been strongly affected by drag folds whose direction of overturn indicates northwestward thrusting.

Correlation of structural features.—The northeastward-trending, subparallel folds, thrust faults, and steeply dipping reverse faults and the northwestward-trending tear faults are attributed to the compressive stresses that marked the Mazatzal Revolution and culminated with the intrusion of the diorite porphyry, Mt. Ord pyroxenite, and pre-Apache granite of central Arizona. These structural features do not involve the Apache, Paleozoic, and later rocks of this region. They affect rocks which, at the head of Maverick Basin and in Four Peaks, are intruded by the pre-Apache granite. The parallelism of the intrusive bodies with the regional structure, as exemplified in the central portion of the range, indicates that their emplacement followed the folding. Furthermore, the above-mentioned folds and faults closely resemble structures of known pre-Apache age in the eastern Tonto Basin area.

As the northeastward-trending normal faults within the range find little expression in the topography, except where followed by stream courses, they are probably related to the Mazatzal Revolution.

PINE CREEK AREA

INTRODUCTORY STATEMENT

The Pine Creek area (Fig. 4) extends southward along Pine Creek from the base of the Mogollon Escarpment to a point 6 miles north of the

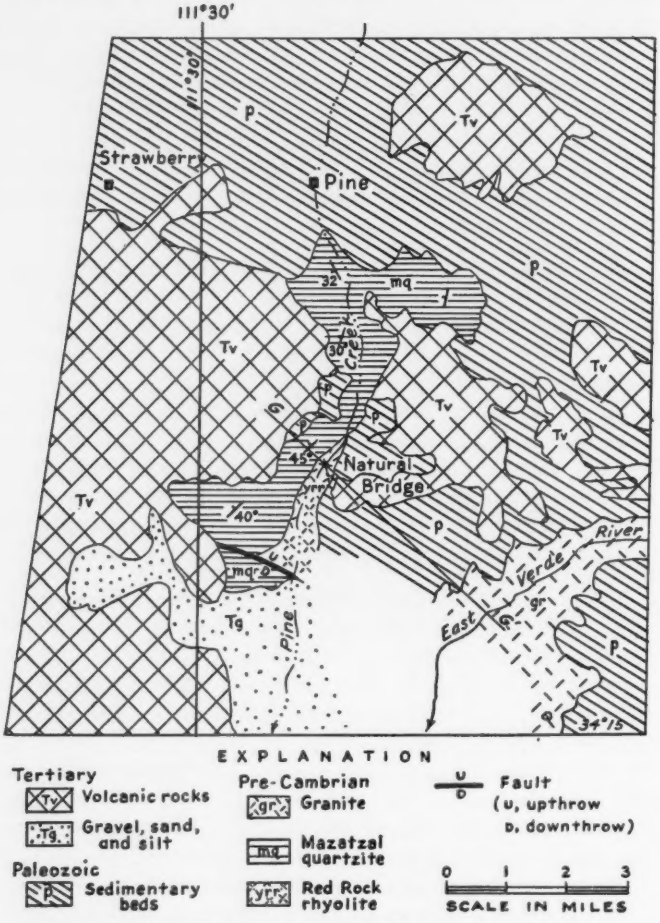


FIGURE 4.—*Generalized geologic map of Pine Creek area*

Mazatzal Mountains. It is accessible by the Payson-Pine road and by a branch road that leads to a summer resort at the picturesque travertine arch known as Natural Bridge.

Here, Pine Creek, a southward-flowing tributary of the East Verde River, has carved a canyon locally 1200 feet deep, affording excellent exposures of pre-Cambrian rocks.

In 1912 Ransome (1916, p. 158-159) recognized that a steep ridge of pre-Cambrian quartzite was unconformably overlapped by Paleozoic strata at Natural Bridge.

During 1920 and 1921 the writer (Wilson, 1922) mapped this area for the Geologic Map of Arizona and measured stratigraphic sections of the quartzite.

Four days were spent in the Pine Creek area during the present investigation, in order to review the stratigraphy and structure of the quartzite and to correlate the underlying formation.

Figure 4, which indicates the general distribution of formations in the Pine Creek area, is based on the Verde reconnaissance topographic sheet (1885) whose scale is inadequate for more than a very generalized expression of the geologic features.

RED ROCK RHYOLITE

The oldest exposed formation consists of chocolate to red-brown locally porphyritic rhyolite which forms the steep-walled inner gorge of Pine Creek Canyon downstream from Natural Bridge. This formation weathers to blocky joint-controlled slopes which, although generally free from soil, give little or no hint as to the original structure.

The porphyritic variety predominates at Natural Bridge but gives way downstream to the typical Red Rock material, characterized by an aphanitic groundmass and small quartz phenocrysts, with only local phases of the porphyritic variety. In places it contains inclusions of altered greenstone.

Although this formation has previously been termed granite (Ransome, 1916, p. 159; Wilson, 1922; Darton, 1925, p. 249) and granite porphyry (Hinds, 1935), its field and microscopic characteristics are essentially identical with those of the Red Rock rhyolite of the Mazatzal Mountains.

MAZATZAL QUARTZITE

In the Pine Creek area no Deadman quartzite and Maverick shale are apparent, but a thick succession of typical Mazatzal quartzite, with prominent basal conglomerate unconformably overlying the Red Rock rhyolite, crops out as an irregular northeastward-trending area, 6½ miles long by 3½ miles wide, which is surrounded and unconformably overlapped by the Paleozoic and Tertiary beds. True to its general type, the Mazatzal quartzite here is characterized by prevailing pale-brown to reddish-

brown color with a distinctive faint purplish tint that is particularly noticeable from a distance. Its thickest exposed section is near the southwestern end of the area, where headward erosion of tributaries to Pine Creek have stripped back the later formations.

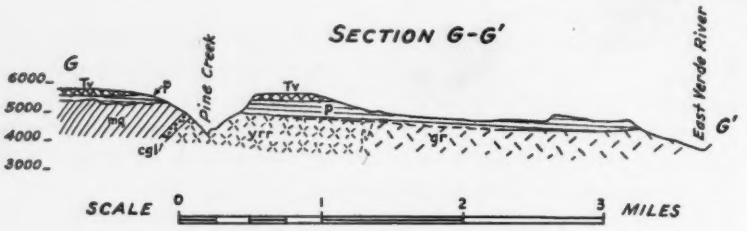


FIGURE 5.—*Sketch section along line G-G' of Figure 4*

yrr, Red Rock rhyolite; mq, Mazatzal quartzite with conglomerate (cgl) at base; gr, granite; P, Paleozoic beds; Tv, Tertiary volcanic rocks.

Section of Mazatzal quartzite near southwestern end of Pine Creek area

	Thickness in feet
(1) Medium- to coarse-grained, banded, cross-bedded, vitreous red-brown and grayish-brown quartzite in beds 1 to 3 feet thick. Conspicuous partings of ripple-marked red shale in lower third	110
(2) Red sandy shale	5
(3) Like (1) but redder and more strongly cross-bedded	100
(4) Like (1) but with thin hematitic sandy partings	60
(5) Medium- to coarse-grained, cross-bedded, sparkling, vitreous brownish-red quartzite, in beds 6 inches to 2 feet thick. Locally contains some sandy to shaly partings	165
(6) Medium- to coarse-grained, cross-bedded, vitreous, sparkling, brownish-red quartzite, in beds 6 inches to 2 feet thick, with fewer sandy to shaly partings than in (5)	60
(7) Alternating fine-grained red quartzite and slabby sandy red shale	30
(8) Fine-grained cross-bedded red quartzite with some sandy shale partings	15
(9) Like (7), with a third to half ripple-marked sandy red shale	95
(10) Fine-grained, cross-bedded, sparkling, vitreous quartzite, in beds 3 inches to a foot thick	30
(11) Like (9) but with less shale	75
(12) Like (10) but fine- to medium-grained and with some sandy red shale partings	70
(13) Fine- to medium-grained, cross-bedded, sparkling, vitreous red-brown quartzite, in beds 6 inches to 2 feet thick with some hematitic sandy partings	180
(14) Like (13) but in beds 2 to 3 feet thick with some thin layers of small, well-rounded quartz pebbles	140
(15) Like (14) but browner; beds 6 inches to a foot thick, weathering more massive in lower portion	655
(16) Thin-bedded sandy member	10
(17) Similar to (15) but contains more conglomeratic beds with generally rounded pebbles of rhyolite, jasper, and quartz up to 1½ inches in diameter; forms reef and weathers grayish brown	50
(18) Like (15) but approximately one third sandy red shale	15
(19) Brownish-red to purplish spotted sandy shale and shaly sandstone	160

		Thickness in feet
(20)	Fine to medium-grained vitreous red-brown quartzite, in beds 6 inches to 2 feet thick, with approximately 30 per cent spotted purplish-red sandy shale	25
(21)	Like (20) but with very little shale	10
(22)	Like (20) but more than 50 per cent shale in upper half	75
(23)	Massive pale-brown reef-forming quartzite with local pebbly layers	70
(24)	Like (23) but in beds 6 inches to 3 feet thick; forms ridge	345
(25)	Similar to (24) but more conglomeratic, with pebbles of rhyolite, jasper, and white quartz; cross-bedded on grand scale; bedding massive and indistinct	70
(26)	Like (25) but in distinct beds 1 to 3 feet thick	285
(27)	Like (26) but redder	325
(28)	Iron-stained, kaolinized rhyolite, spherulitic in places (estimated)	75
(29)	Fine- to medium-grained, locally pebbly, hard, vitreous grayish-brown quartzite (estimated)	200
(30)	Grayish-brown arkosic conglomerate with rounded to subangular pebbles, less than an inch to more than a foot in diameter, of Red Rock rhyolite, quartzite, and jasper. Rests on eroded surface of Red Rock rhyolite	300
	Total thickness of section	3805

Thin sections of samples taken from 12 different beds of Mazatzal quartzite in the Pine Creek area show microscopic features typical of the formation as described elsewhere in this paper.

Microscopically the interbedded rhyolite member shows corroded, altered phenocrysts of orthoclase, up to 5 mm. in diameter, in an altered, siliceous, microcrystalline groundmass. The feldspars of the rock have been extensively replaced by kaolin. Much secondary quartz and finely divided iron oxide have developed in the groundmass.

The thick basal conglomerate with its coarse angular boulders, predominantly of Red Rock rhyolite, indicates the proximity of a pre-Mazatzal highland. As no conglomerate of such thickness and with boulders of such size and angularity occurs in the Mazatzal Mountains section, this highland probably rose northwestward. The nondeposition of the Maverick in the Pine Creek area is in accord with its northward thinning in the Mazatzal Mountains.

Although the intraformational rhyolitic member (28) shows no evidence of erosion, it probably represents a flow that was erupted during a brief pause in sedimentation, rather than a sill. It lacks cross-cutting relations and effected no appreciable metamorphism of the quartzite. In places it shows chilled borders and swirling flow lines. Furthermore, its spherulites (Grout, 1932, p. 232) are indicative of a surface flow with glassy groundmass.

GRANITE

Medium- to coarse-grained pinkish-brown granite, unconformably overlain by Paleozoic and Tertiary beds, forms the gorge of the East Verde River in this area (Fig. 4). It is microscopically identical to the prevailing type of pre-Cambrian granite of central Arizona.

STRUCTURE

The Mazatzal quartzite of the Pine Creek area constitutes a northeastward-trending ridge flanked by unconformably overlapping Paleozoic and Tertiary formations (Figs. 4, 5). This ridge disappears beneath the Carboniferous strata of the Plateau on the northeast and is limited by pre-Pliocene Tertiary graben step faults on the southwest. These faults may represent renewed movement upon zones of weakness which were developed during the Mazatzal Revolution.

The quartzite beds constituting the ridge in general strike northeastward and dip 35° to 55° NW. (Pl. 8, fig. 2), but in the northwestern portion of the area they deviate somewhat from this attitude, as shown in Figure 4. They are broken at right angles to the strike by numerous joints and small faults along which notable sericitization and deposition of specularite have taken place. In the northwestern portion of the area the Mazatzal quartzite has been cut by a fault that strikes northeastward and dips 70° NW.

The old quartzite ridge is either a fault block or the eroded limb of a fold. In either case it was upheaved prior to Paleozoic sedimentation, probably during the Mazatzal Revolution, as part of the great northeastward-trending mountain range of which the pre-Cambrian rocks of the present Mazatzal Mountains, eastern Tonto Basin, and Del Rio areas are remnants. The northwestward-striking faults and joints may have been initiated as shear breaks resulting from the compressive forces of the Mazatzal Revolution. The steeply northwestward dipping fault in the northwestern portion of the area may have been formed upon release of the compressional stresses.

EASTERN TONTO BASIN AREA

INTRODUCTION

The eastern Tonto Basin area (Fig. 6) extends along the base of the Mogollon escarpment between Tonto Creek on the west and Pleasant Valley on the east.

In this area the principal topographic feature is Christopher Mountain which trends eastward from the head of Tonto Creek to Gordon Canyon, between the Pleasant Valley trail on the south and the foot of the Mogollon escarpment on the north. This mountain rises steeply from an altitude of 5000 feet at Tonto Creek to a long, narrow mesa crest with an altitude of 6500 to 6800 feet. The mountain has steep slopes, dissected by numerous small canyons, but its top, composed essentially of hard, resistant Mazatzal quartzite, has withstood well the erosion to which it has been subjected since denudation in Tertiary and Quaternary time.

During 1920 and 1921 the writer found quartzite of Mazatzal type unconformably overlapped by Younger pre-Cambrian and Paleozoic rocks in the northeastern portion of the area (Wilson, 1922, p. 307).

Darton (1925, p. 234-236), after careful examination of the Gordon Canyon and Haigler Creek localities, published a brief description of the relations of the pre-Cambrian and Paleozoic formations there.

Five days were spent in the eastern Tonto Basin area for the present investigation, in order to check the previous observations that the Mazatzal quartzite had been deformed in pre-Apache time and to determine the relations of the pre-Cambrian igneous rocks to the Mazatzal Revolution in this area. As the only topographic maps available for the region were the old Verde and Holbrook reconnaissance sheets, on a scale of 1 : 250,000, Figure 6 is merely a tentative sketch.

The eastern Tonto Basin area is made up largely of pre-Cambrian rocks of the same general lithology and structure as those of the Mazatzal Range from which they represent a northeastward continuation. They include Red Rock rhyolite, Mazatzal quartzite, and granite, unconformably overlain by Apache beds. The Paleozoic strata of the Plateau unconformably overlap the pre-Cambrian formations on the north. Loosely consolidated gravel, sand, and silt of Tertiary and Quaternary ages mantle much of the southeastern portion of the area.

RED ROCK RHYOLITE

The rhyolite appears in two irregular areas (Fig. 6). That of upper Haigler Creek was termed "granite" by Darton (1925, p. 235; *cf.* Hinds, 1938).

The rhyolite of eastern Tonto Basin is largely of extrusive aspect. It locally reveals well-defined flows and agglomeratic phases but generally is homogeneous, dense, and without apparent bedding planes. Some specimens contain numerous fragmental, fine-textured spherulites up to 1.5 mm. in diameter, indicating that it is a surface flow.

In the vicinity of the granite contact, abundant fine-grained secondary quartz and some epidote have been developed.

Microscopically, this rhyolite closely resembles typical Red Rock rhyolite.

MAZATZAL QUARTZITE

In the eastern Tonto Basin area no Deadman quartzite and Maverick shale are exposed, but more than 1000 feet of typical Mazatzal quarzite is faulted against, and presumably overlies, Red Rock rhyolite.

The quartzite is prevailingly pale brown to reddish brown, thick to thin bedded, fine to coarse grained, prevailingly cross-bedded, very hard and vitreous, locally ripple marked, and in places contains thin partings

of arenaceous spotted maroon shale of which some are marked by desiccation cracks. It closely resembles the typical Mazatzal quartzite of the Mazatzal Mountains.

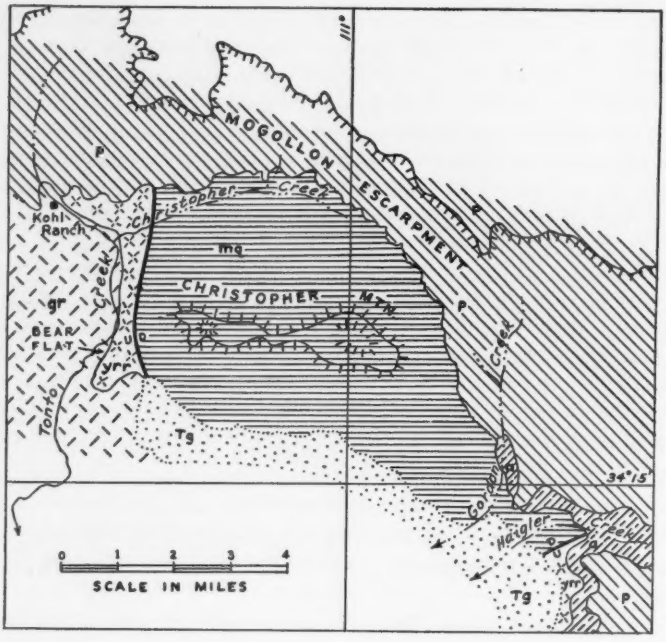


FIGURE 6.—*Geologic sketch map of eastern Tonto Basin area*

GRANITE

In eastern Tonto Basin a batholithic mass of granite unconformably underlies the Paleozoic and Apache strata on the north and east. On Upper Tonto Creek, 1¼ miles downstream from Kohl's ranch, the granite in-

trudes a small fault block of typical Mazatzal quartzite. East of upper Tonto Creek and southeast of Bear Flat it intrudes the Red Rock rhyolite. For more than 100 feet away from this contact it shows a fine-grained border phase and locally includes blocks of the rhyolite.

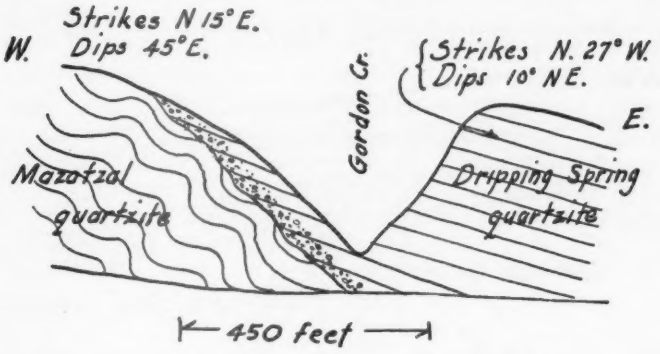


FIGURE 7.—*Sketch section showing relations in Gordon Canyon*

This granite is a pinkish-brown coarse-grained holocrystalline rock consisting largely of pink feldspar and grayish-white quartz. Microscopically, the feldspar is entirely orthoclase and microperthite. It is poor in ferromagnesian minerals. Sericite, kaolin, and iron oxide are rather abundant as alteration products, and cloudy masses of limonite and an undetermined amorphous grayish-white mineral occur interstitially. The rock very closely resembles the normal pre-Cambrian granite of the Mazatzal Mountains.

APACHE GROUP

Strata of the Apache group unconformably overlap the Red Rock rhyolite on upper Haigler Creek and the Mazatzal quartzite in Haigler and Gordon canyons (Figs. 7, 8).

The lowest exposed Apache formation is Dripping Spring quartzite which, near the contact with the Mazatzal quartzite and Red Rock rhyolite, is conglomeratic. On Haigler Creek the contact is marked by a basal or marginal conglomerate, approximately 100 feet thick, of oval to angular and domino-shaped pebbles in a sparse arkosic cement. The pebbles, which range from an inch up to 4 feet in diameter, are mostly of Mazatzal quartzite with a few small ones of oxidized Red Rock rhyolite.

The Dripping Spring quartzite is overlain by 80 to 100 feet of altered, siliceous, locally shaly Mescal limestone, overlain in turn by Paleozoic strata.

STRUCTURE

The pre-Apache formations of eastern Tonto Basin constitute part of the northeastward-trending mountain range, already referred to, which was upheaved during the Mazatzal Revolution, long before Apache time.

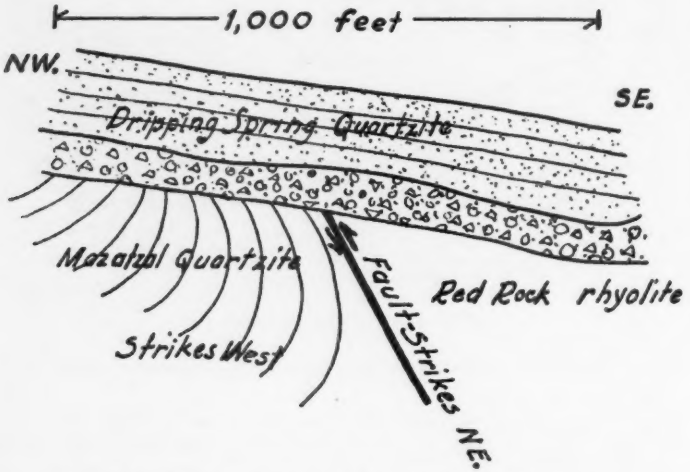


FIGURE 8.—*Sketch section showing relations in Haigler Canyon*

The Red Rock rhyolite shows several systems of joints of which the strongest strikes northeastward, and a weaker one northwestward. Rather intense northeastward jointing prevails in the granite.

In the canyon of Gordon Creek the Mazatzal quartzite strikes N. 15° E. and has a general dip of 45° SE., whereas the Dripping Spring quartzite that unconformably overlaps it strikes N. 27° W. and dips 10° NE., flattening considerably northeastward. The Mazatzal strata show large-scale drag folds, in contrast to the overlying uncrenulated Apache strata.

On the northern side of Haigler Creek the Mazatzal quartzite lies in an anticline whose limbs dip 45 degrees. It appears to be upturned in the vicinity of a reverse fault that strikes N. 60° E., dips 60° SE., and brings Red Rock rhyolite on the hanging-wall side against Mazatzal quartzite (Pl. 7, fig. 2; Fig. 8). The rhyolite near this fault is silicified, and the quartzite for more than 150 feet away from it is much shattered. The conglomerate and Dripping Spring beds that unconformably overlap the northeastern limb strike N. 45° W. and dip 20° NE., flattening considerably northeastward. They also overlap the rhyolite but are nowhere displaced by the fault; hence its movement is of pre-Apache age.

Northeast of Bear Flat and east of Tonto Creek the Mazatzal quarzite of Christopher Mountain is faulted against Red Rock rhyolite on the southwest and west. This fault contact, which trends about S. 10° W. and swings southeastward across the ridge east of Bear Flat, is characterized by rather extensive shearing in both formations. Its southeastern segment appears to be a steeply dipping reverse fault that northwestward passes into the zone of a shear fault. The quartzite of the mountain lies in gentle north-northeastward-trending folds, locally complicated by steeply dipping reverse and normal faults which, in all probability, closely followed the folding and granitic intrusion as a phase of the Mazatzal Revolution. The tilting of the Apache beds in the northeastern part of the area may be interpreted as having resulted from later local uplift, possibly associated with intrusion of the diabase; Darton (1925, p. 234) infers that it was of pre-Troy age.

DEL RIO AREA

INTRODUCTION

The Del Rio pre-Cambrian area (Fig. 9) is on Granite Creek, a mile east of Del Rio and 20 miles north of Prescott.

This section of country represents the northwestern extremity of the Black Hills Range, which, as Lindgren (1926, p. 8) states, appears to be a horst. Granite Creek has bisected the pre-Cambrian area with a meandering, northwestward-trending shallow canyon whose course has been determined largely by structure. Near the northern end of the area the Verde River has carved a shallow canyon whose meandering, east-northeastward course seemed to be determined, at least in part, by local structures within the Paleozoic strata.

During 1920 and 1921 the writer (Wilson, 1922) mapped the Del Rio area for the Geologic Map of Arizona and correlated the pre-Cambrian quartzite there with the Mazatzal quartzite of the Mazatzal Mountains.

Three days were spent in the Del Rio area for the present investigation, in order to review the structure of the pre-Cambrian quartzite and its relations to the Paleozoic.

ALDER SERIES

Near the mouth of Granite Creek (Fig. 9) is a northeastward-trending area, three-quarters of a mile long by an eighth of a mile wide, of generally fine grained, well-laminated, dark-gray to brown phyllite and argillaceous sandstone of Alder type. It is unconformably overlain by the Paleozoic and Tertiary beds and faulted against Mazatzal quartzite on the northeast.

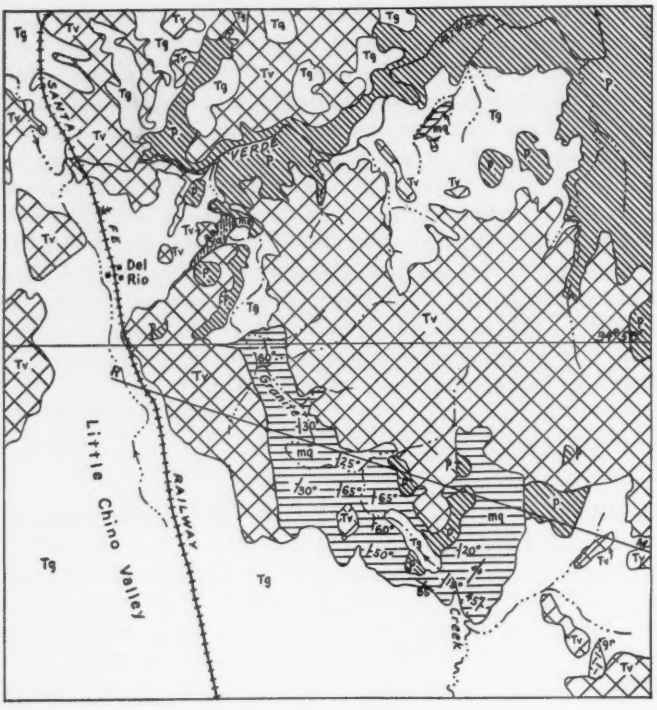


FIGURE 9.—*Geologic map of the Del Rio area*

MAZATZAL QUARTZITE

The Mazatzal quartzite here is faulted against the Alder series and unconformably overlapped by Cambrian sandstone, Devonian limestone,

Tertiary and Quaternary sedimentary beds, and Tertiary volcanic rocks.

The following section of the quartzite was measured by tape, beginning with the stratigraphically highest exposed member in the western part of the area:

Section of Mazatzal quartzite east of Del Rio

	Thickness in feet
(1) Medium- to fine-grained, generally sorted, cross-bedded, hard, vitreous light-gray quartzite, in beds 1 to 5 feet thick	250
(2) Alternating cross-bedded, hard, vitreous red-brown massive quartzite and conglomeratic beds with oval to subangular pebbles, ranging from a quarter of an inch to 3 inches in diameter, of quartzite, white quartz, red jasper, and red slate. Lower 35 feet contains parting bands of arkosic, ripple-marked red shale	185
(3) Conglomeratic light-gray quartzite with pebbles up to 6 inches in diameter	50
(4) Similar to (3) but with sparser pebbles in a rusty-red cement	250
(5) Like (4) but somewhat more vitreous and lighter colored. Pebbles generally less than an inch in diameter	275
(6) Coarse-grained, cross-bedded, slabby red quartzite, locally sandy and banded	40
(7) Fine-grained, cross-bedded, hard, vitreous light-brown to gray quartzite	160
(8) Similar to (7) but coarser-grained to conglomeratic with rounded pebbles, up to an inch in diameter, mainly of white quartz	70
(9) Coarse-grained, cross-bedded, locally conglomeratic dark-brown sandstone with some reddish bands. Bands of spotted red shale in lower portion	265
(10) Conglomerate of unassorted subangular to rounded pebbles, an eighth of an inch to 6 inches in diameter, of white quartz, red jasper, and slate in a coarse arkosic cement	85
(11) Coarse-grained, cross-bedded, hard vitreous gray to light-brown quartzite, locally streaked with magnetite and hematite	150
(Sequence is interrupted here by a fault that strikes N. 20° E. and dips 10° N.W.)	
Total thickness of section	1780

East of the fault that ends the section, there appears to be several hundred feet of quartzite beds, stratigraphically higher than (1), which weather blackish.

An outstanding feature of the Mazatzal quartzite of the Del Rio area is the prevalence of fine, well-rounded to subangular pebbles of white quartz. At the time of its deposition, therefore, a fairly high, rugged land mass with many exposed quartz veins existed in the vicinity.

GRANITE

A small mass of aplitic granite, bounded by Tertiary sedimentary and volcanic beds, crops out in the southeastern part of the area (Fig. 9). It is lithologically similar to aplitic phases of the pre-Cambrian granite of central Arizona and is believed to be of pre-Cambrian age.

STRUCTURE

The beds of pre-Cambrian Alder series exposed in the Del Rio area strike N. 45° E. and dip 50° NW. The Mazatzal quartzite against which they are faulted has similar strike and dip. The quartzite of the

main area, as shown by Figure 9 and Section R-M, lies in broad folds of prevailing northeastward trend, with limbs of moderate to steep dip and N. 40° E. to N. 20° W. strike. These folds are locally associated with northeastward-striking thrust faults (Pl. 3, fig. 1). At its southwestern margin the quartzite has been steeply to vertically upturned (*see* Figure 9), presumably by a northwestward-trending fault whose trace is concealed by alluvium.

Most of the Paleozoic strata lie essentially flat but in the southeastern portion of the area strike northwestward and dip 20° NE. They overlap the roughly eroded folds of the Mazatzal quartzite with a very marked discordance in structure, proving that the principal folding and faulting in the pre-Cambrian formations took place prior to deposition of the lowest Paleozoic formation—the Middle Cambrian Tapeats sandstone. The trend of the folds, the attitude of the pre-Cambrian strata, and the strike of the thrust faults are all characteristic of the Mazatzal Revolution.

SOUTHERN BLACK HILLS

GENERAL STATEMENT

The Black Hills comprise a horst range, 25 miles long by a maximum of 10 miles wide, that trends northwestward from Cherry Creek to the Verde River, between the Verde Valley on the northeast and the Agua Fria or Lonesome Valley on the southwest.

This range, which contains the great pre-Cambrian copper deposits of Jerome in its northeastern portion, the Yaeger copper deposit at its southwestern base, the Cherry Creek pre-Cambrian auriferous veins on the south, and numerous small prospects, has received considerable attention from mining geologists.

In 1919 and 1920 a geologic reconnaissance map (Lindgren, 1926, pl. 1) of the Jerome quadrangle was made by Olaf P. Jenkins and the writer, for the Arizona Bureau of Mines. During parts of 1925-1930 detailed mapping of the geology was carried on by the Arizona Bureau of Mines, with Carl Lausen beginning a study of the pre-Cambrian rocks and the writer separating the Paleozoic and later formations.

The Black Hills consist of a basement of pre-Cambrian rocks unconformably overlain by about 2300 feet of Cambrian to Permian strata, locally capped by Tertiary basalt. It attains a maximum elevation of 7720 feet above sea level or 4400 feet above the Verde River. Its northeastern front represents a precipitously eroded fault zone along which approximately 2400 feet of vertical displacement occurred in pre-Cambrian time and about 1600 feet since the eruption of the Tertiary basalt (Reber, 1938, p. 51). These later movements have involved the lacustrine

and gravelly sedimentary beds (Jenkins, 1923) of probable Pliocene age that occur in the Verde Valley. The southwestern slope of the range also represents an eroded fault zone of pre-Cambrian to late Tertiary age.

The pre-Cambrian rocks consist largely of greenstone, rhyolitic, and sedimentary schists, intruded by diorite, granite porphyry, and rhyolite porphyry, and limited on the south by intrusive contact with a batholithic mass of granite analogous to the Bradshaw granite of the Bradshaw Mountains. Although much detailed work remains to be done before the structural relations of these pre-Cambrian formations can be fully understood, it has been shown that in pre-Cambrian time, probably before the advent of the principal intrusions, the schists were compressed into close folds of prevailing north-northeastward trend and affected by locally complex faulting.

Considerable pre-Cambrian faulting also followed the intrusions. Owing to these structural complexities and also to obscurity of the contacts, the local relations are not readily apparent. Reber (1920), followed by Hansen (1930), regarded the greenstone as older than the sedimentary schist, while Lausen (1930) cited what he regarded as unconformities to prove that the greenstone is younger and is in turn overlain by the rhyolite. On the other hand, Lindgren (1930) suggested that Lausen's break between the sedimentary and greenstone schists may represent an ancient fault.

RESULTS OF PRESENT INVESTIGATION

Although a detailed study of the pre-Cambrian formations of the Black Hills is beyond the scope of the present investigation, the discordance of opinion regarding the pre-Cambrian structure necessitated an examination of the age relations. Accordingly, seven trips were made into the southwestern portion of the range in search of the unconformity and the contrasts in grades of metamorphism that Lausen featured there. Five days were spent examining the greenstone in the central portion, south of Mt. Mingus, and the rhyolite in the southeastern portion of the range.

As a result of this work it is concluded that the greenstone of the Mazatzal Mountains may be correlated with the intermediate to mafic rocks of the "greenstone complex" of the Black Hills. This portion of the "complex" is termed the Yaeger greenstone in this paper.

The rhyolitic portion of the "greenstone complex" is commonly a pale-brown to gray rock which shows small phenocrysts of clear quartz and white feldspar in an abundant, dense, fine-grained groundmass. It is identical in field appearance and microscopic features with typical Red Rock rhyolite, with which it may reasonably be correlated.

The sedimentary schist, which has been intruded locally by narrow dikes of diorite porphyry, consists of thinly laminated, brown to brown-

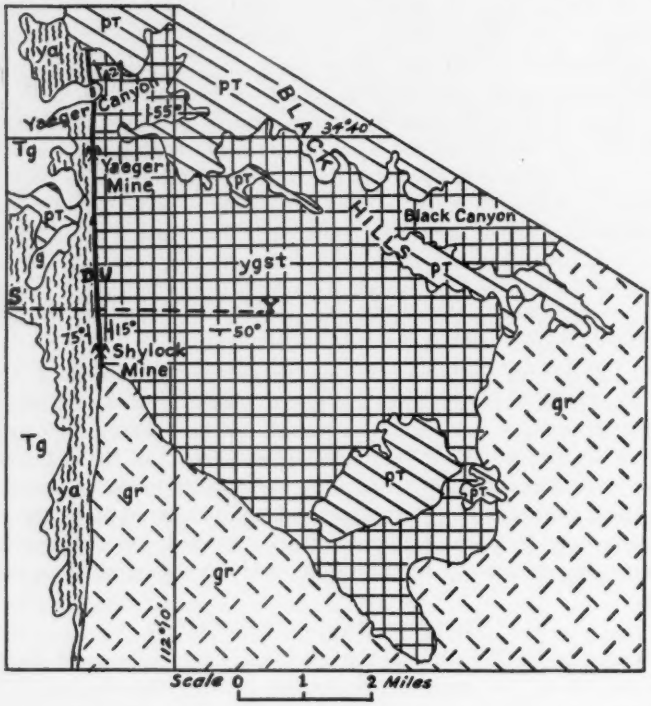


FIGURE 10.—*Geologic map of southern portion of Black Hills*
Modified from map by Carl Lausen and Eldred D. Wilson.

ish-red slate and phyllite with some arkosic sandstone and a prominent bed of squeezed conglomerate composed of well-worn pebbles, mainly of quartz, jasper, and rhyolite in a fine-grained siliceous, sericitic cement.

As these metamorphosed sedimentary rocks bear a striking field resemblance to the Alder series of the Mazatzal Range, they are correlated with that formation.

The field work failed to demonstrate that the greenstone unconformably overlies the sedimentary schist. On the contrary, a steeply dipping

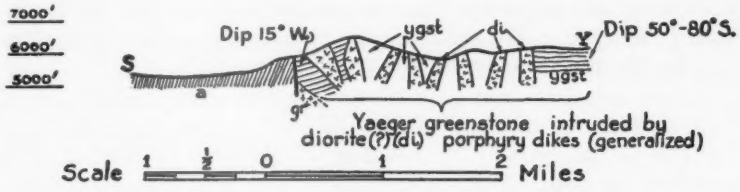


FIGURE 11.—*Sketch section along line S-Y of Figure 10*

or vertical fault of northward strike separates the two formations throughout a distance of more than 4 miles, with intermittent exposures extending from the mantle of Paleozoic beds north of Yaeger Canyon to the granite tongue an eighth of a mile south of the Shylock mine. This granite (Fig. 10), which intrudes the greenstone and extends westward to the southern projection of the fault zone, is doubtless responsible for at least part of the hydrothermal metamorphism that has affected both the Alder series and the Yaeger greenstone in this area.

Immediately east of the fault the greenstone consists of coarse-grained, intensely sheared, clastic beds which strike northward and dip 15° to 75° W. They have been intensely chloritized and carbonatized and weather pale yellowish brown to dull green. Intruding them are large irregular dikes of dense, dark rock which dominate the landscape. Examined microscopically, this rock shows skeletal phenocrysts of entirely sericitized feldspars in a fine-grained chloritic, sericitic groundmass.

In the central portion of the area, south of Mt. Mingus and 2 to 4 miles east of the Shylock mine, the greenstone contains relatively more recognizable volcanic members and has been extensively intruded by large dikes of diorite porphyry. There its bedding strikes N. 60° E. and dips steeply southeastward.

No definite evidence for the relative ages of the rhyolite and the greenstone was obtained. Wherever seen together, these two formations are in fault contact.

The prevailing lamination of the Alder series, which closely parallels original bedding, strikes N. 20° E. and dips steeply to almost vertically.

It is concluded that the principal structures in the southern portion of the Black Hills Range resulted from the Mazatzal Revolution. Large,

closed folds, such as are characteristic of the Mazatzal Revolution, appear to have involved the Yaeger greenstone and Alder series, whose beds prevailingly strike northeastward to northward and dip steeply. In all probability, the Red Rock rhyolite of the area was also involved in this folding. The faults that separate the Yaeger greenstone from the Red Rock rhyolite and Alder series strike northeastward to northward. These structures are earlier than the Paleozoic beds and also, insofar as known, earlier than the pre-Cambrian granite; hence their correlation with the Mazatzal Revolution seems highly probable.

SUMMARY

CORRELATION

In this paper the two major systems or types of pre-Cambrian rocks have been referred to simply as Older and Younger pre-Cambrian without use of the terms "Archean" and "Algonkian".

The pre-Cambrian rocks of central Arizona have a recognizable stratigraphy, divisible as follows (*see also* Table 1):

Younger pre-Cambrian
- Apache group (unconformably overlaps Mazatzal quartzite in the Eastern Tonto Basin)
- Post-Mazatzal erosion interval during which batholithic masses of granite were uncovered and deeply dissected

Mazatzal Revolution and igneous invasion, particularly of granite

Older pre-Cambrian
- City Creek series (missing in most places; stratigraphic position uncertain; not found in contact with Mazatzal quartzite)
- Mazatzal quartzite
- Maverick shale (in Mazatzal Mountains only)
- Deadman quartzite (in Mazatzal Mountains only; rests only on Red Rock rhyolite)
- Post-Yavapai erosion interval during which areas of Red Rock rhyolite were laid bare and deeply oxidized
- Regional uplift
- Yavapai group (formerly termed Yavapai schist)
  - Alder series (not found in normal contact with Deadman or Mazatzal quartzites; believed to have been removed from some areas of Red Rock rhyolite during the post-Yavapai erosion interval
  - Red Rock rhyolite (unconformably overlain by Deadman quartzite in Mazatzal Mountains and by Mazatzal quartzite in the Pine Creek or Natural Bridge area)
  - Yaeger greenstone; base not seen

During early reconnaissance work in the region, the Red Rock rhyolite was generally classed as schist, but at Natural Bridge (Ransome, 1916, p. 159; Wilson, 1922, p. 299-312) and in the Eastern Tonto Basin (Darton,

1925, p. 234-235) it was mistaken for granite. Likewise, pebbles of this rock in the conglomerate of the Mazatzal quartzite were mistaken for granite and aplite. Hinds (1935, p. 10) referred to the Red Rock rhyolite at Natural Bridge as "granite porphyry" and to conglomerate pebbles of this same rock as "granite" and "aplite," but later (Hinds, 1936, p. 96-97) termed it "metarhyolite."

STRUCTURAL EVENTS

The vulcanism that formed the Yaeger greenstone and Red Rock rhyolite was doubtless marked by crustal unrest, but the resultant deformation is obscure. After deposition of the Alder beds the region underwent uplift, accompanied probably by faulting, but this deformation is inferred rather than recognized. Contrary to the interpretations by Hinds (1935, 1936, 1938), no major intrusions of pre-Mazatzal granite have been recognized. Evidence for his "Arizonan" revolution (Hinds, 1936, p. 100; 1938, p. 445-448) seems to be lacking in the central Arizona region studied.

After deposition of the Mazatzal quartzite and long before Apache sedimentation, the region underwent a profound crustal disturbance, termed the Mazatzal Revolution. As a result, the Mazatzal quartzite and older formations, including rocks heretofore mapped as Yavapai and Pinal schist, are affected by subparallel folds, thrust faults, and imbricate, steeply dipping reverse faults, generally of northeastward to northward trend. Parallel to and later than these structures are stocks and dikes of dioritic to pyroxenitic composition and the largest masses of granite exposed in the region. This granite has rather distinctive field and petrographic features. In the Mazatzal Mountains it is definitely of post-Mazatzal—pre-Apache age.

The regional compression induced lamination and slaty cleavage in the incompetent rocks but no marked recrystallization. Strong schistosity is apparent only in the vicinity of the larger intrusive bodies.

A crustal disturbance of such magnitude as the Mazatzal Revolution doubtless involved a region much larger than central Arizona. Ransome (1916, p. 165-166) and Stoyanow (1936, p. 462) have shown that the pre-Cambrian rocks of the Mazatzal Range and eastern Tonto Basin made up a northeastward-trending land mass throughout a large part of Paleozoic time. Stoyanow terms it Mazatzal land, a possible extension of Schuchert's Ensenada land.

It is suggested that the Mazatzal Revolution produced the northeastward- to northward-trending structures that characterize the pre-Apache and pre-Unkar formations throughout Arizona. Its close folding would give a rigid and positive character to the areas affected.

The central Arizona region underwent no great deformation between the Mazatzal Revolution and the Tertiary Basin and Range orogeny.

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ORDOVICIAN-SILURIAN RELATIONS IN PENNSYLVANIA

BY BRADFORD WILLARD AND ARTHUR B. CLEAVES

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ABSTRACT

New data on the Ordovician-Silurian relations in Pennsylvania make possible reinterpretation of long-known facts. These data were obtained through the reopening of abandoned railway tunnels in south-central Pennsylvania and in highway construction elsewhere. It appears now that the term Oswego was misapplied in Pennsylvania. There is probably little or no true Oswego in the State. For beds commonly referred to by that name, the term Bald Eagle is revived and treated as basal Juniata. There is a disconformity between the Bald Eagle and the Tuscarora east of the Susquehanna River and either a disconformity or unconformity below the Bald Eagle or Tuscarora or Shawangunk from the Susquehanna River into southeastern New York. Either hiatus might be used as a convenient Ordovician-Silurian line of separation. If the lower is accepted, it puts the Juniata in the Silurian; if the upper be used, then the Juniata becomes Ordovician. The magnitude of the lower hiatus and the structural data associated with it indicate that the Taconic disturbance affected Pennsylvania probably as far west as the Susquehanna Valley.

INTRODUCTION

To the problem of Ordovician-Silurian relations in Pennsylvania, R. S. Bassler, Charles Butts, B. L. Miller, Charles Schuchert, G. W. Stose, C. K. and F. M. Swartz, and others have contributed. Within the last 2 years new information has been collected by the present authors in regard to the position of the Ordovician-Silurian boundary and the Taconic Disturbance. The authors are not prepared to say the last word on these topics but offer the new data for what they may be worth.

About 50 years ago the South Penn Railroad Company planned a low-grade line across the mountains of southwestern Pennsylvania. Between Chambersburg and Pittsburgh several tunnels were started. The railroad was abandoned before completion, but some of the tunnels were dug for considerable distances into, and one completely through, the mountains. Recently a project was started to clean out, enlarge, and convert the tunnels into a modern highway across the Appalachians of Pennsylvania. The Pennsylvania Topographic and Geologic Survey was called upon for geologic advice. The junior author was assigned to this task and made bed-by-bed investigations of the old borings, three of which involve the Ordovician-Silurian relations and are here recorded. For the first time in the State a nearly entire section of the Upper Ordovician Martinsburg shales, the overlying formations, and their interrelations are known in a single section, for the tunnels are superior to any recognized surface exposures.

About the time of the tunnel reopening the highway along the west side of the Susquehanna River north of Harrisburg was rebuilt. On the face of Kittatinny Mountain a complete section from the Upper Ordovician shales through the Lower Silurian has been cut. It has furnished a quite different interpretation of the local geology. The outstanding facts shown by this section have been recorded (Willard and Cleaves, 1938).

The senior author has worked intermittently upon the Ordovician and Silurian in Pennsylvania. In 1937 P. E. Raymond accompanied him in the field. Dr. Raymond at present has the entire collection of Martinsburg fossils exclusive of the graptolites which have been submitted to Dr. Rudolf Ruedemann. Because the fossils are not fully studied, it is impossible to cite the revised faunal lists which eventually will be prepared. The junior author has occasionally worked with the senior author on the Ordovician-Silurian problems, particularly in northeastern Cumberland County, a region included in an area which he mapped (Cleaves, 1933).

PREVIOUS WORK

Henry D. Rogers, a century ago, recognized the important Paleozoic divisions in Pennsylvania and in 1858 gave the following Upper Ordovician, Lower Silurian sequence:

Levant white sandstone (Divisions II, III, IV of New York Medina)
Levant red sandstone (Division I of New York Medina)
Levant gray sandstone (Oneida conglomerate of New York)
Matinal shale and slate (Hudson River and Utica of New York)

Equivalences in New York are as indicated parenthetically by Rogers himself.

In the closing years of the Second Pennsylvania Geological Survey, J. P. Lesley (1892-1895) wrote:

Formation IV	Medina white sandstone
	Medina red sandstone
	Oneida conglomerate
Formation III	Hudson River shale and slate

At that time the true relations between the Oneida and Medina were not understood. Lesley summarized considerable detail regarding these divisions. He recognized for the first time certain sandstones in the Hudson River (now Martinsburg) shales and drew the base of Formation IV at the bottom of the first massive sandstone above the slates and shales of III. The top was placed at the upper surface of the highest massive white sandstone. He remarked that the three members of Formation IV were grouped together on "topographical grounds"—that is, physiographic expression—but he believed them separable stratigraphically. Lesley's description of the "Oneida" gray sandstone (or conglomerate) shows that he recognized the individuality of this unit:

> "This iron speckled aspect of the *Oneida* division of Formation No. IV is characteristic of it throughout the central region of the State, and it is a peculiarity which marks it quite as plainly as the flagstone slides mark the *Medina upper* divisions." (Lesley, 1892-1895, vol. I, p. 661.)

In 1909 Stose's account of the Mercersburg and Chambersburg Folio appeared. This was the first modern interpretation of the Ordovician shales in Pennsylvania. He recognized the following sequence:

	Feet
Tuscarora sandstone. Massive, granular white quartz sandstone	270
Juniata formation. Soft red sandstone and shale with some hard quartz sandstone and conglomerate	400–500
Martinsburg shale. At top, a sandstone member. Upper part soft, greenish, arkosic sandstone. Below, chiefly dark shale, black, carbonaceous, fissile to blocky at the base; dark-gray crumbly "shoe-peg" shale, some weathering to soft whitish clay, in the upper portion	2000

Stose split the Martinsburg into two parts distinguished lithologically, the upper part being the sandier. A sandstone member at the top he described as follows (Stose, 1909, p. 10):

"The uppermost portion of the formation is a soft sandstone of a yellowish-green color. In the broad shale belt west of Chambersburg, where it is exceptionally hard, coarse-grained, thick-bedded, and easily recognized, the sandstone member has been mapped, but elsewhere its outcrops are inconspicuous and not readily distinguished from the shale. In places along the steep eastern escarpment of the plateau the massive beds produce rugged and picturesque ravines. This rock, when fresh, is a greenish-gray arkose composed of grains of sand and feldspar; the latter has been decomposed to kaolin, giving the rock a speckled appearance. Toward the base it is interbedded with shale and merges into the shale below."

Stose recorded a few fossils from the upper part of the shaly Martinsburg, identified by Ulrich as Eden. With the exception of *Rafinesquina alternata*, Stose mentioned none from the topmost sandstone. His description of the sandstone as speckled is important, because this character has impressed all observers since Lesley's day.

Bassler (1919, p. 157) subdivided the sequence of the Lower Silurian and Upper Ordovician in southern Pennsylvania and Maryland as follows:

	Feet
Juniata formation of earliest Silurian or highest Ordovician age	
Martinsburg shale	
Upper Maysville division	
Unfossiliferous sandstone (Oswego sandstone). (Probably represented under cover west of North Mountain, in Maryland)	150
Lower Maysville division	
Fossiliferous gray sandstone with *Orthorhynchula linneyi* bed at top. (Probably present west of North Mountain)	300
Eden division	
Yellow shale and calcareous sandstone interbedded, with upper Eden fossils	500±
Soft greenish to yellow shaly sandstone and shale with Eden fossils not uncommon at several horizons	500±

Bassler (1919, p. 169) offers the most complete lists of fossils published for this region. Since material collected by the authors is not yet ready to publish, the following list of his Eden fauna is quoted:

Climacograptus bicornis (Hall) var.
Diplograptus vespertinus (Ruedemann)
Cornulites flexuosus (Hall)
Heterocrinus heterodactylus Hall
Merocrinus species undetermined
Hudsonaster clarki n. sp.
Berenicea vesiculosa Ulrich
Bythopora arctipora (Nicholson)
Hallopora onealli sigillarioides (Nichelson)
Bastostoma jamesi Nichelson
Arthropora cleavelandi (James)
Pholidops cincinnatiensis Hall
Dalmanella multisecta (Meek)
Plectorthis plicatella Hall var.
Strophomena hallie (S. A. Miller)
Strophomena sinuata James var.
Rafinesquina squamula (James)
Plectambonites rugosus (Meek)
Leptaena gibbosa (James)
Zygospira modesta (Hall)
Ctenodonta obliqua Hall
Ctenodonta filistriata Ulrich
Clidophorus planulatus (Conrad)
Byssonychia vera Ulrich
Lyrodesma conradi Ulrich
Sinuites cancellatus (Hall)
Sinuites granistriatus (Ulrich)
Tetranota obsoleta Ulrich
Hormotoma gracilis (Hall)
Lophospira (Ruedemannia) lirata (Ulrich)
Liospira micula (Hall)
Orthoceras transversum Miller
Cryptolithus bellulus (Ulrich)
Cryptolithus recurvus (Ulrich) n. sp.
Triarthrus becki Green
Isotelus stegops Green
Calymene granulosa (Foerste)
Aparchites minutissimus (Hall)
Ceratopsis chambersi (Miller)
Ulrichia bivertex (Ulrich)
Bythocypris cylindrica (Hall)
Lepidocoleus jamesi (Hall and Whitfield)

Bassler added greatly to our knowledge of the fossils of the late Ordovician in the Chambersburg region in that he gave us a list from the

Orthorhynchula bed. This is Stose's arkosic sandstone.[1] (Bassler, 1919, p. 170):

Lingula nicklesi n. sp.
Plectorthis plicatella Hall
Rafinesquina alternata (Emmons)
Rafinesquina squamula (James)
Orthorhynchula linneyi (James)
Zygospira modesta (Hall)
Zygospira ? errecta (Hall)
Ischyrodonta unionoides (Meek)
Pterinea (Caritodens) demissa (Conrad)
Byssonychia radiata (Hall)
Byssonychia praecursa Ulrich
Allonychia ovata Ulrich
Modiolopsis modiolaris (Conrad)
Modiolodon truncatus (Hall)
Orthodesma nasutum (Conrad)
Liospira micula (Hall)
Orthoceras lamellosum Hall
Isotelus megistos Locke

Along the west slope of Tuscarora Mountain, southeast of McConnellsburg, Pennsylvania, Bassler (1919, p. 173) recognized the following sequence:

	Feet
Silurian—Tuscarora sandstone	
Massive, granular, white quartz sandstone	200+
Ordovician or Silurian—Juniata formation	
Soft red unfossiliferous sandstone and red shale, interbedded	400+
Ordovician—Martinsburg shale	
Oswego gray sandstone member	150
Maysville (Fairview) fossiliferous gray sandstone (*Orthorhynchula* bed at top)	300
Upper Eden shale and calcareous sandstone interbedded	400

To the upper 150 feet of Martinsburg included in beds which Stose designated as the sandy uppermost Martinsburg, Bassler applied the name Oswego sandstone of late Maysville age. An *Orthorhynchula* zone at the top of the underlying standstone is widespread and important in Pennsylvania. To the older sandy beds in Pennsylvania and Maryland Bassler applied the Ohio name, Fairview. He noted that the shaly Martinsburg and the beds which he called Fairview and Oswego are all mutually transitional.

Recently Stose (1930) has added to the knowledge of the Ordovician sandstone overlying the shaly Martinsburg, particularly in eastern Pennsylvania between the Schuylkill and the Lehigh River. The eastern sandstone appears to be the correlate of the Fairview but it was not given a geographic name by Stose.

In central Pennsylvania, Upper Ordovician shales, practically the correlate of the Martinsburg, are known as the Reedsville. Recent practice (Butts, 1918; Butts and Moore, 1936) has restricted these to beds below the "Oswego" as defined by Bassler to the south. The principal distinction between the Reedsville and Martinsburg is that the base of the latter is somewhat older. The Reedsville has recently been newly described by Butts and Moore (1936) in the Bellefonte quadrangle, Pennsylvania. Butts's account of the Tyrone quadrangle has been available to the authors and is now in press with the Pennsylvania State Survey.

[1] Not the highest sandstone from which Stose recorded *R. alternata*. All other investigators report this as barren.

As in the Martinsburg to the south, a sandstone in the upper Reedsville grades upward into the speckled "Oswego" sandstone. (Butts and Moore use the term Oswego.) This sandstone is correlated with the upper Martinsburg (Fairview) sandstone by its stratigraphic position and the occurrence of the *Orthorhynchula* bed. The "Oswego" is barren, arkosic sandstone and local conglomerate, tough, brown to gray with reddish beds. As the gray beds weather, brown, rusty spots appear from the decomposition of pyrite, producing the characteristic speckled appearance. This unit rests upon the *Orthorhynchula*-bearing sandstone.

Central Pennsylvania is the type region of the Bald Eagle conglomerate named and described by Grabau (1909; 1913). The name takes precedence over the use of Oswego as applied in Pennsylvania. It has received some recognition but it is now rejected by the United States Geological Survey (Wilmarth, 1938). Grabau described the Bald Eagle as white or gray, occasionally red conglomerate and quartzitic sandstone, strongly cross-bedded and varying in thickness from 550 to 1319 feet. It was called "Oneida" by the Second Pennsylvania Survey workers, but Grabau maintained that it is of Lorraine age. He (Grabau, 1913) later correlated the Bald Eagle in part at least with the Oswego sandstone of New York and dated it as probably late Pulaski or even younger.

From south-central Pennsylvania (Chambersburg region) eastward, the accounts of Ordovician-Silurian relations in Pennsylvania may be summarized briefly. Between Chambersburg and the Susquehanna, comparatively little has been published on the Ordovician-Silurian relations. From the Susquehanna to the Delaware, across New Jersey into New York, the late Ordovician and early Silurian formations have been studied for years. At Susquehanna Gap north of Harrisburg the accounts of Stose (1930) and of Swartz and Swartz (1931) indicate that prior to recent highway excavations the white, conglomeratic Tuscarora sandstone overlay a few feet of Juniata red beds, whose exact thickness was unknown and whose base was hidden. Some distance south the shaly Martinsburg cropped out. Stose considered this section (along the west shore) to be a conformable sequence. At Swatara Gap the relations were better exposed than on the Susquehanna River (Stose, 1930; Swartz and Swartz, 1930). Fossiliferous Eden shale at the top of the Martinsburg was found in contact with beds assigned to the basal Tuscarora. The section on the Schuylkill, north of Hamburg, shows the Martinsburg-Tuscarora contact. Unfossiliferous, sandy beds presumed to be upper Martinsburg lie approximately horizontal and butt against a vertical wall of upturned Tuscarora sandstone and conglomerate. The angle of discordance is approximately 90 degrees. Observers have dis-

agreed as to whether the contact is entirely the result of faulting, is purely an "angular unconformity," or a combination of both.

The section on the Lehigh River is completely exposed only on the Lehigh and New England Railroad along the east side of Lehigh Gap south of Palmerton. Here, previous investigators (Stose, 1930; Swartz and Swartz, 1931; Behre, 1933; Willard, 1938) have observed the sequence. The Martinsburg beds underlie unconformably what has been called the basal conglomerate of the Tuscarora formation. The angle of discordance is only a few degrees. There is scant published evidence as to the age of the exposed Martinsburg. Farther east in Pennsylvania additional contacts have not been generally recognized. At Little Gap, Wind Gap, and Delaware Water Gap, the contact is usually recorded as concealed. Schuchert (1916) mentioned an exposure of this contact at the Delaware River, but others have been unable to rediscover it. It has been generally presumed that the Martinsburg shale is directly overlain by the basal Silurian. In the sections from the Delaware River eastward, Swartz and Swartz (1930) reported that it is not possible satisfactorily to separate the Tuscarora from the rest of the Medinan, so that the inclusive term Shawangunk is applicable to the Silurian below the red Bloomsburg.

In New Jersey the relations appear to be unconformable between the Shawangunk or its correlate—the Green Pond conglomerate—and underlying formations. The subjacent beds vary greatly in age: along Kittatinny Mountain they are probably all shaly Martinsburg, perhaps older than any recorded at this contact in Pennsylvania (Weller, 1903; Lewis and Kümmel, 1915, 1931); in the isolated Green Pond Mountain syncline of north-central New Jersey, the Green Pond conglomerate was reported by Lewis and Kümmel (1915) and by Kümmel and Weller (1902) to rest locally upon the pre-Cambrian gneiss or Cambro-Ordovician limestone; at Otisville, New York, the Shawangunk lies in angular discordance upon shaly Martinsburg strata, whose age is not definitely known.

Table 1 shows some of the more important interpretations which have been made of the Ordovician-Silurian relations in Pennsylvania and neighboring States.

RECENT OBSERVATIONS

FRANKLIN AND FULTON COUNTIES

The authors made observations all across Pennsylvania from Franklin and Fulton counties to the Delaware Water Gap, across northern New Jersey, and into New York. Except for the three tunnel sections, all data were obtained from surface exposures. In Franklin and Fulton counties the sections were worked across Cove and Tuscarora mountains.

TABLE 1.—*Comparison of recognized Ordovician-Silurian sequences*

GENERAL			H. D. ROGERS 1858	J. P. LESLEY 1892–1895	STOSE 1909 South-central Pa.		BASSLER 1919 South-central Pa., Md.		BUTTS and MOORE Central Pa.		OHIO	NEW YORK	NEW JERSEY
Medinan			Levant white sandstone	Medina white sandstone	Tuscarora sandstone		Tuscarora sandstone		Tuscarora sandstone		Brassfield	Medina	Shawangunk or Green Pond
Richmond			Levant red sandstone	Medina red sandstone	Juniata formation		Juniata formation		Juniata formation		Richmond	Queenston	
Cincinnatian	Maysville	McMillan	Levant gray sandstone	Oneida conglomerate	Martinsburg shale	Upper-sandstone	Martinsburg shale	Oswego sandstone	Oswego sandstone*		McMillan	Oswego	Martinsburg
		Fairview						Fairview sandstone	Reedsville shale	Sandstone with *Orthorhynchula*	Fairview	Pulaski	
	Eden	Frankfort	Matinal shale and slate	Hudson River shale and slate		Shale of Eden age		Shale of Eden age		Shale of Eden age	Eden	Frankfort	
		Utica										Utica	

* Bald Eagle of Grabau.

Elsewhere, practically every section which was studied crosses Kittatinny Mountain.

Since Stose (1909) studied the Mercersburg-Chambersburg area, two highways over Cove and Tuscarora mountains east of McConnellsburg

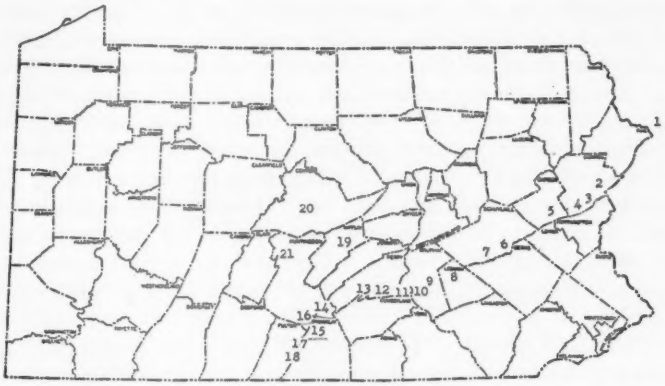

FIGURE 1.—*Sketch map*

Showing localities furnishing information on Silurian-Ordovician relations. All are in Pennsylvania except as indicated. 1. Otisville, N. Y., 2. Delaware Water Gap, 3. Wind Gap, 4. Little Gap, 5. Lehigh Gap, 6. Schuylkill Gap, 7. Little Swatara notch, 8. Swatara Gap (and Little Mountain), 9. Heckert Gap, 10. Susquehanna Gap, east, 11. Susquehanna Gap, west, 12. Sterretts Gap, 13. Doubling Gap, 14. East Blue Mountain tunnel, 15. West Kittatinny Mountain tunnel, 16. East Tuscarora Mountain tunnel, 17. McConnellsburg-Fort Loudon road, 18. McConnellsburg-Mercersburg road, 19. Kishacoquillas Gap, 20. Bellefonte, 21. Tyrone.

have been improved, and new cuts have been opened. These afford good, though incomplete, sections in the Upper Ordovician and Lower Silurian. Except that more fossils (as yet not fully identified) were collected, little additional data were found beyond those of Stose (1909) and Bassler (1919). No evidence of any stratigraphic break in the entire sequence was discovered. There is no doubt that the shaly, upper Martinsburg of Eden age passes above into sandstone of lower Maysville (Pulaski) correlation. Overlying this, in apparent conformity or transitional contact, is the Bald Eagle sandstone ("Oswego" of Bassler). It is a relatively coarse, barren sandstone in which pebbles may occur though sparingly in this part of Pennsylvania. When fresh, it is gray to greenish gray, but the weathered rock is speckled with small brown or rusty spots attributed to the oxidation of pyrite. (Stose thought this was due to weathering of feldspar; other observers ascribe it to weathering of pyrite or limonite.)

It is not improbable that in Franklin and Fulton counties this sandstone is in part the time equivalent of the typical Oswego of New York. However, it is barren and conformably overlain by unfossiliferous red beds of the Juniata formation. The New York Oswego is fossiliferous, grades down into the Pulaski shale, and is disconformably overlain by the Queenston red beds, an acknowledged correlate of the Juniata. It is not possible to prove through actual tracing or a succession of adjacent sections that these beds are the correlative of the New York Oswego, and there is no known paleontologic means of correlation. Except in south-central sections, they rest unconformably upon underlying strata but are transitional upward into the Juniata. For these reasons the authors doubt the advisability of using Oswego in Pennsylvania. They prefer to revive the local term Bald Eagle (Grabau, 1909). It is identical to or the correlate of beds which have been called Oswego in central and south-central Pennsylvania. The Bald Eagle varies from sandstone to conglomerate, always with the same peculiar lithology distinguishing it—the speckled sandstone, or, if pebbly to conglomeratic, a speckled, sandy matrix. The authors use Bald Eagle as the Bald Eagle member of the Juniata formation. This is a new application of the term and is somewhat restrictive. The reason for this will be shown presently. The Martinsburg is therefore confined to the underlying beds, thus differing from the use of Stose (1909) and Bassler (1919) who included the Bald Eagle ("Oswego") in the Martinsburg. In so restricting the top of the Martinsburg, the authors are in agreement with Butts and Moore (1936) in their restriction of the term Reedsville. (*See* Table 1.) The Bald Eagle grades upward into the red Juniata. The Juniata red shale and sandstone in highway sections across the mountains west of Chambersburg contain little or no conglomerate. Like the Bald Eagle, the red beds are totally devoid of fossils, but the Fairview sandstone of the upper Martinsburg is fossiliferous. The Juniata red beds grade up into the white Tuscarora sandstone whose age is attested by the presence of *Arthrophycus*. This fossil is not abundant east of McConnellsburg but is common in the Tuscarora in northern Franklin County. From the foregoing it is seen that there is apparently a conformable sequence from beds of Eden age into the Lower Silurian.

The junior author is wholly responsible for the data from the tunnels. He has added to the knowledge of the sequences, has corroborated surface observations that all formations are transitionally related, and obtained precise determinations of thicknesses. The sequences in the three tunnels are given. In each the Fairview is treated as the upper member of the Martinsburg. The Bald Eagle is considered the basal member of the Juniata.

EAST BLUE MOUNTAIN TUNNEL

The geologic sequence exposed or explored by drilling from east to west in East Blue Mountain tunnel is: (1) Martinsburg shale, (2) Bald Eagle sandstone, (3) Juniata red beds, (4) Tuscarora sandstone. The beds dip steeply and a horizontal diamond drill bore hole has been made completely through the Juniata formation and the Tuscarora quartzite. The true thickness of the Juniata is shown below. The Tuscarora is repeated by two strike faults so that its recorded thickness of 956 feet is excessive.

Columnar Section of Strata Exposed or Explored by Diamond Drill in East Blue Mountain Tunnel

	Thickness in feet
Tuscarora formation	
White, quartzitic sandstone, some repetition by faulting	956
Juniata formation	
Gray, granular sandstone and occasional beds of red sandstone. Transitional zone into Tuscarora quartzite, penetrated by diamond drill	46.2
Juniata red sandstone proper. Massive, red sandstone, some beds quartzitic, many beds micaceous; occasional interbeds of soft, red shale 2 to 4 inches thick. The upper 117 feet of this sandstone was determined by diamond drilling	729
Bald Eagle member. Top transitional with red Juniata; below the transition, massive-bedded, green to gray, coarse sandstone, sometimes speckled with tiny limonitic spots. No conglomerate	115
Transitional zone with Martinsburg upper sandstones and interbedded sandstone and shale; perhaps more properly included in Fairview member, but unfossiliferous	33
Martinsburg formation	
Fairview member. Interbedded dark-gray, medium- to fine-grained sandstone and characteristic gray-green and black Martinsburg shale	204
Eden and older, gray to black and greenish-gray, thin-bedded shale, sometimes arenaceous. There is a one-foot bed of fossiliferous, crystalline limestone 304 feet below the top of the Martinsburg. Included in this thickness is 264 feet of Martinsburg exposed in the approach cut. An abundant fauna was collected just outside the portal	910

The relationships of the Martinsburg, Bald Eagle, Juniata, and Tuscarora are all transitional. There is no evidence of unconformity, and, therefore, no indication of the Taconic Disturbance in this region.

WEST KITTATINNY MOUNTAIN TUNNEL

The stratigraphic units exposed in the West Kittatinny Mountain tunnel are: (1) Martinsburg, (2) Bald Eagle, and (3) the red Juniata (in part). A horizontal diamond drill hole through the balance of the Juniata not exposed in the old workings and the Tuscarora beyond the red beds between the present headings completes the section.

Columnar Section of Strata Exposed in West Kittatinny Mountain Tunnel and in the Undriven Section of the Tunnel

	Thickness in feet
Tuscarora formation	
White quartzitic sandstone and white quartz sandstone. The Rose Hill-Tuscarora transition beds in East Tunnel are included	486
Juniata formation	
Massive red sandstone and quartzitic sandstone, sometimes micaceous; occasional half an inch to an inch interbeds of soft, red shale. This thickness includes a 44-foot Tuscarora-Juniata transition zone	774
Bald Eagle member. At top, transitional zone in the Juniata. Below transition, massive-bedded, greenish to light-gray sandstone, sometimes speckled with tiny limonitic spots. Beds up to 2 feet thick	118
Transitional zone with Martinsburg upper sandstone, the Fairview member	50
Martinsburg formation	
Fairview member. Sandstone and shale which grade gradually into the underlying, dark shales	246
Eden and older, alternate dark-gray, medium- to fine-grained sandstone and interbeds of fossiliferous, crinoidal limestone. The limestone beds vary between an eighth of an inch and 3 feet thick and continue through the Martinsburg to about 400 feet below the Bald Eagle. Typical, dark-green to black shale below	1320*

* This figure includes the beds exposed at the approach cut to this tunnel.

The transitional relations between all the formations in this tunnel preclude the occurrence of the Taconic Disturbance.

EAST TUSCARORA MOUNTAIN TUNNEL

The geologic formations and subdivisions exposed in East Tuscarora are: (1) Martinsburg, (2) Bald Eagle, and (3) lower Juniata red beds. A horizontal diamond drill has been driven through the rest of Juniata red sandstone and the Tuscarora white quartzite from the existing heading which is in the Juniata to the station of the heading in the west tunnel.

	Thickness in feet
Tuscarora formation	
White quartzitic sandstone including the Rose Hill transitional zone above	509
Juniata formation	
Juniata-Tuscarora transition zone at top, 243 feet thick. Below, massive-bedded, red sandstone with thin red shale interbeds, 577 feet	820
Bald Eagle member. Greenish, massive-bedded sandstone. Interbedded greenish-black and black shale and hard, massive-bedded sandstone and arenaceous shale transitional below characteristic Bald Eagle. Transitional beds at top with red Juniata, 19 feet	124
Martinsburg formation	
Fairview member. Massive-bedded, dark-gray sandstone and greenish-black shale. Fossiliferous at base with *Byssonychia*	135
Eden and older dark-green to black shale, locally silicified, becoming fissile toward the base. The upper 800 feet contain an occasional interbedded, blue-gray, crystalline, fossiliferous limestone in beds an eighth of an inch to 6 inches thick. Some of the highest limestones are argillaceous and slightly pyritiferous. There is included herein 82 feet exposed in the approach cut	1183

As in the other two tunnels, the formations are transitional to one another, again precluding the possibility of the Taconic disturbance here.

DOUBLING AND STERRETTS GAPS

East from Franklin and Fulton counties to the Susquehanna River, surface sections show the Ordovician-Silurian relations. On the road across Kittatinny Mountain at Doubling Gap in southwestern Perry County, near the mountain crest, the Tuscarora white sandstone or quartzite overlies the Juniata red sandstone. The two are lithologically identical. They are distinguished by a gradual color change. As it is impossible to mark precisely their contact, it is arbitrarily drawn at the top of the highest red beds. Down the south slope into Cumberland County, the Juniata is exposed in a long road section. Below the 1000-foot contour, no red beds occur in place. At a sharp bend in the road at this elevation is the highest Martinsburg encountered. It is shale and thin sandstone of Eden age. Between these and the lowest exposure of the red Juniata, in the gutter on the west side of the road, is characteristic, rusty-speckled, greenish-gray Bald Eagle sandstone. The Bald Eagle and red Juniata are unfossiliferous except for vertical tubes filled with sand ("fucoids" or "worm borings") near the top of the red beds. The Tuscarora on the road north from the mountain crest contains *Arthrophycus*. The Martinsburg-Bald Eagle and the Bald Eagle-red Juniata contacts are hidden. There may be a disconformity at the top of the Martinsburg, for no trace was found of the Fairview sandstone; the highest Martinsburg beds carry an Eden fauna and are not dominated by sandstone, and no *Orthorhynchula* zone of the Fairview sandstone was identified. As a check on this sequence, a section was visited across Conococheague Mountain in the western part of Perry County where the road from Hemlocks State Forest Park crosses to Doylesburg. The Bald Eagle is better exposed than at Doubling Gap, but its contacts are obscured. Here, alternate thin sandstone and dark shale with Eden fossils are among the highest exposed Martinsburg beds, but no Fairview sandstone was found.

A few miles east of Doubling Gap a partial section shows at Sterretts Gap in Cumberland County north of Carlisle. The white Tuscarora sandstone is exposed at the mountain crest and is transitional with the underlying red Juniata to the south. Neither Bald Eagle nor Fairview was seen in the concealed interval separating the lowest red beds from shaly Martinsburg. The latter is exposed in road cuts at the foot of the mountain. It carries Eden fossils collected and identified by the junior author as follows (Willard and Cleaves, 1938, p. 6):

"Crinoidea", columnals
Pholidops cincinnatiensis
Plectorthis plicata
"Dalmanella" multisecta
Sowerbyella sericea
Leptaena gibbosa
Zygospira modesta
Bilobites ?
Ctenodonta fillistriata
Clidophorus planulatus
Modiolopsis ?
Cryptolithus bellulus
Calymene sp. ind.
Triarthrus eatoni
T. sp. ind.

SUSQUEHANNA GAP

During 1937 and 1938 the highway along the west side of the Susquehanna River opposite Harrisburg was rebuilt, and a complete section through the nearly vertical beds of Kittatinny Mountain was exposed at the first water gap. Formerly, on the railroad, one saw only the Tuscarora and a few feet of the Juniata red beds, and, some distance south, shaly Martinsburg (Stose, 1930; Swartz and Swartz, 1931). Today, the entire face of the mountain is sliced off so that all strata from the upper Martinsburg through the Tuscarora show. Stratigraphic features never before known in this part of the State are exposed. The authors (Willard and Cleaves, 1938, Pl. 10) have published a brief account of the sequence and here amplify that description.

The Tuscarora is white to gray, more or less quartzitic sandstone and conglomerate with *Arthrophycus* rare. It is transitional with red Juniata sandstone below to the south. The Juniata has some interbedded shale, and most of the lower half of its 80 feet is coarse red conglomerate. The red beds are transitional downward into the Bald Eagle member.[2] These beds are important because of their peculiar and unmistakable lithology. Many of the rounded, well-sorted pebbles suggest derivation from some of the sandstones in the Martinsburg. They are cemented by a weak matrix. Both the matrix and the nonconglomeratic sandstone beds are arkosic, rather coarse sand. In a fresh sample they are gray or greenish gray; when weathered they assume the characteristic brown-speckled appearance typical of the Bald Eagle to the west and northwest. The rock breaks down readily, the conglomerate yielding loose pebbles. Even when fairly fresh, a hammer blow separates the phenoclasts cleanly from the matrix. This character is observable in the Bald Eagle conglomerate in all of its exposures to the east of the Susquehanna River.

The Bald Eagle overlies dark Martinsburg shale which is fossiliferous through the topmost bed. The fauna is of Eden age. So sharp is the contact between the Martinsburg and Bald Eagle that it is possible to insert a knife blade between the two formations; there is no measurable angular discordance of dip, however. At the top of the Martinsburg the change is abrupt from the soft, clayey shale to coarse Bald Eagle. The upper few inches of the shale is leached to light gray or buff owing

[2] Willard and Cleaves (1938) referred to this member as "Oswego" because its true relations were uncertain at the time they wrote their original description of the Susquehanna Gap section.

to percolating water along the nearly vertical beds. No evidence of movement was discovered at this contact, yet sandy beds such as are assigned to the Fairview to the west are absent, and no example of *Orthorhynchula* was found.

Summing up the section, we have:

	Thickness in feet
Tuscarora white sandstone and conglomerate	275
Juniata red beds	80
Bald Eagle gray sandstone and conglomerate	30
Martinsburg shale, Eden age	

The new data from this section include precise thickness determinations. The Tuscarora carries *Arthrophycus*. The red Juniata is conglomeratic, and its relation to the Tuscarora is transitional. It is here that the Bald Eagle was first recognized so far east at this latitude. Also it is conglomeratic, a feature which ties it in with the type Bald Eagle to the northwest. It agrees with its lithology farther east. On the other hand, the sandstones and matrix of the Bald Eagle simulate the lithology of the less conglomeratic exposures to the west and southwest. Because of this combination of characters, the Bald Eagle on the west side of Susquehanna Gap is intermediate between the beds of this member at other localities. Through displaying here features confined to single exposures elsewhere, the Bald Eagle north of Harrisburg is indispensable as a means of tying together somewhat dissimilar lithologies.

The Fairview sandstone and the *Orthorhynchula* zone are absent. The Martinsburg beds of Eden age are overlain disconformably by the Bald Eagle. The application eastward of these data puts an entirely new and different interpretation upon the sections; it is because of the evidence revealed at the Susquehanna River and eastward that the authors include the Bald Eagle as the basal Juniata member. The two are transitional, but the Bald Eagle is separated from the Martinsburg by a hiatus, which is greater to the east.

Along the east bank of the Susquehanna River at Rockville, an incomplete section exposed in cuts on the Pennsylvania Railroad has been long known. The strata are shattered, overturned northward, and cut by a number of faults. At the southern end, the lowest bed exposed is a coarse conglomerate. The pebbles are well rounded, well sorted, and lodged in a weak, sandy matrix speckled with iron rust spots. The conglomerate turns rusty on long-exposed surfaces, although it is gray or greenish gray when fresh. It had been regarded as basal Tuscarora or perhaps Juniata but now, by analogy with the sections to the west, it is unhesitatingly called Bald Eagle. It is faulted against the next higher beds in the section. Most of these are hard, quartzitic, gray Tuscarora sandstone and conglomerate or conglomerite with the pebbles and matrix welded securely together in sharp contrast to the weak Bald Eagle which

may be easily hammered apart. The faulting has introduced into the lower part of this section a few red beds assigned to the Juniata, though apparently transitional with the Tuscarora. It is impossible, because of the structure, to determine the red Juniata-Bald Eagle relations. Because the Martinsburg is concealed for half a mile south along the railroad, nothing can be said of its lithology, fossils, or relations to younger formations.

SECTIONS BETWEEN THE SUSQUEHANNA AND THE SCHUYLKILL

Until 1938, no Juniata red beds were known east of the Susquehanna. The senior author had observed a little red float rock about one-tenth of a mile east of the river along the south slope of Kittatinny Mountain but hesitated to declare its identity since it might have come from the red beds of the Rose Hill sandstone which forms the mountain crest here.

During the summer of 1938, two graduate students from Northwestern University, R. M. Foose and H. Barnes, studied the structure of Kittatinny Mountain from the Susquehanna Valley eastward for a few miles. The authors spent some time in the field with these men. At Heckert Gap, a wind gap 7 miles east of the Susquehanna River, Foose and Barnes discovered red sandstone float and red soil so situated and of such lithology as to be almost certainly derived from the Juniata, although the Juniata was not seen in place. This, then, is to date the easternmost indication of any red Juniata. The Bald Eagle is not exposed at Heckert Gap (Foose, 1939).

Where Swatara Creek breaks through Kittatinny Mountain in northern Lebanon County, a good section is exposed along the west side of the valley at the water gap. This section has been described by Swartz and Swartz (1930; 1931) and Stose (1930). A small quarry and highway cuts expose the highest Martinsburg and the base of the overlying formation. The Martinsburg is dark, highly fossiliferous shale of (middle?) Eden age. Stose (1930, p. 643) listed the following faunule:

Diplograptus sp.
Spatiopora lineata
Ectenocrinus simplex
Heterocrinus sp.
Pholidops cincinnatiensis
Dalmanella emacerata
D. multisecta
Sowerbyella aff. *sericea*
S. aff. *plicatella*
Rafinesquina ulrichi
Leptaena gibbosa
Ctenodonta filistriata
Cleidophorus planulata
Rhytimya producta
Calpomya faba
Cuneamya cf. *neglecta* (Eden form.)
Archinacella patelliformis
Sinuites cancellatus
Liospira micula (Eden var.)
Lophospira ohioensis
Orthoceras aff. *transversum*
Cornulites aff. *flexuosus*
Jonesella crepidiformis
Ceratopsis chambersi
Primitia cf. *bivertex*
Primiticella unicornis
Elpe radiata
Cryptolithus bellulus
C. tesselatus (Eden var.)
Calymene granulosa
Triarthrus becki (Eden var.)
Tornquistia sp.

The authors confirm Stose's findings in that the "upper sandy member" of the Martinsburg is absent. Resting in slight unconformity (not greater than 5 degrees discordance) upon Martinsburg shale, the whole upturned nearly to the vertical, is coarse conglomerate. The evidence from the new section north of Harrisburg assigns this stratum by analogy to the Bald Eagle member of the Juniata rather than to "basal Tuscarora," as it has been considered. The lithology is identical with the Bald Eagle except that there are more quartz phenoclasts among the coarse but well-rounded, well-sorted pebbles, which are lodged in a matrix of greenish-gray, arkosic sand weathering brownish flecked. The rock is weak and easily shattered. A specimen which the senior author placed in his rock garden (prior to recognizing its true identity) partly disintegrated in 4 or 5 years to sand and pebbles. From Swatara Creek east only conglomerate has been found in the Bald Eagle member.

The slight divergence of dips between the Bald Eagle and the Martinsburg is the only significant difference between this contact and that on the Susquehanna River, but it is important in the light of what is known to the east. It is the first structural hint of the Taconic Disturbance so far west in Pennsylvania. Stose did not report this slight discordance, and the authors found it only after road improvements had more fully exposed the beds adjacent to the contact.

The Bald Eagle conglomerate, 10 to 12 feet thick at Swatara Gap, is conformable with overlying beds. It is directly overlain by the Tuscarora, although no discordance of dips was measured at this contact. The hard, quartzitic Tuscarora sandstone and pebble beds are partly hidden by talus, but *Arthrophycus* has been here reported from near the top of the formation or at the base of the Clinton. Evidently, since they are mutually parallel, the Tuscarora and Bald Eagle are disconformably related, for there is no trace of the red Juniata between them.

Across Swatara Creek at the Gap, the section is buried under heavy talus. About 2 miles southeast of the Gap, however, important data were collected in Little Mountain (*cf.* Stose, 1930). The western end is next to the creek, and the ridge extends eastward parallel to Kittatinny Mountain for 4 or 5 miles across Lebanon County. On a long-abandoned canal which skirts the western end of Little Mountain, the exposed beds are steeply upturned, heavy sandstones, devoid, insofar as known, of fossils. Based upon the senior author's detailed studies of neighboring sections showing sequences in the higher Martinsburg they are a probable correlate of the Fairview sandstone (Willard, 1939). If these beds represent the Fairview sandstone, they are post-Eden in age and younger than any beds seen in the Martinsburg at Swatara Gap. Little Mountain is capped by an outlier of Bald Eagle and Tuscarora.

Whether this is downfaulted or downfolded is uncertain. Along the crest nothing was surely seen in place amidst a veritable felsenmeer of Tuscarora sandstone chunks. Among these in a high point near the western end of the crest an example of *Arthrophycus* was found. About 2 miles east of the creek an improved road crosses Little Mountain. Cuts in the Martinsburg are inconclusive, but on the north slope where the road makes a broad curve toward the crest Bald Eagle float was found. The parent ledge could not be discovered among the dense vegetation and talus or float rock. The lithology again is characteristic coarse conglomerate of rounded pebbles in a gray-green, arkosic sandstone matrix which gives the usual rusty-speckled weathering. No red Juniata was discovered.

Between Swatara and Schuylkill gaps there are several wind gaps and notches opening toward the south slope of Kittatinny Mountain. At none was a complete section showing the Ordovician-Silurian relations observed. North-northwest of Bethel in a notch in the headwaters of the West Branch of Little Swatara Creek, the Tuscarora is in place. Among its float is undoubted *Arthrophycus*. With the boulders of white quartzite and sandstone, there are also a very few examples of Bald Eagle conglomerate, identical lithologically to that at Swatara Gap. It was not seen in place, and nothing could be determined of its relations to the Martinsburg. The East Branch of Little Swatara Creek has cut back a notch north of Schubert. A recently constructed highway across the mountain along the east side of this notch furnishes exposures of only the Tuscarora. Along the west side of the notch are abandoned quarries, almost hidden among trees and talus. Here the basal Tuscarora is characteristic, hard, white to gray, quartzitic sandstone and pebble beds. In the westernmost quarry, it rests disconformably upon 6 or 7 feet of coarse, rusty-weathering, gray-green conglomerate of well-sorted, well-rounded pebbles lodged in an arkosic sandstone matrix with rusty speckles. Samples compared with the Bald Eagle at Swatara and Susquehanna gaps were found to be identical. As at Swatara, the Tuscarora rests disconformably upon the Bald Eagle. The basal contact of the Bald Eagle with the Martinsburg is exposed, but the soft, dark shale has so deeply weathered that it was not possible to determine even its attitude, nor were fossils found in it. No sandstone was seen in the section below the Bald Eagle conglomerate. Other notches visited in northwestern Berks County expose merely great Tuscarora talus slopes which cover everything down into the Martinsburg shale.

SCHUYLKILL GAP

Although the authors offer no new data on the section at Schuylkill Gap, a modified interpretation is suggested for the sequence there. Dur-

ing the summers of 1937 and 1938, J. R. Moseley of Wayne University studied the Martinsburg in this vicinity. He has submitted to the Pennsylvania State Survey a map and summary of his findings. His work corroborates and expands that of Stose (1930) and of the authors. The data now presented have been observed or checked by the authors and were known prior to Moseley's study.

Along the east side of the Schuylkill, north of Hamburg for about a mile, extensive highway cuts and abandoned quarries have exposed Upper Ordovician massive sandstone. It passes northeastward under the Tuscarora sandstone in a spur of Kittatinny Mountain called the Pinnacle which rises about 6 miles east of Schuylkill Gap. The sandstone emerges to the east thereof in Shochary Ridge and the hills southward of that ridge in northeastern Berks County. The sandstones in these high areas are distributed along several parallel synclines whose axes trend approximately east-west and presumably continue to the river. The sandstones are by structure and stratigraphic position the youngest Ordovician beds in Berks County. Stose (1930, p. 648-649) reported a Pulaski fauna from them at the crest of Shochary Ridge:

Rafinesquina small, aff. *camerata*
Rafinesquina cf. *alternistriata*
Rafinesquina aff. *ulrichi*
Strophomena n. sp. (coarsely striated like *S. sinuata*)
Sowerbyella aff. *sericea*
Dalmanella aff. *multisecta*
Dalmanella sp.
Zygospira modesta
Ctenodonta cf. *levata*
Other small pelecypods
Sinuites aff. *cancellatus*
Tetranota sp.
Liospira aff. *progne*
Lophospira aff. *obliqua*
Lepidocoleus jamesi
Calymene sp.
Proetus aff. *parviusculus*
Ctenobolbina cf. *ciliata*

Older, black shales north of Shochary Ridge carry Eden fossils. Stose believed that the late Ordovician sandstone in northern Berks County might be separable lithologically into two parts, but it is convenient to treat it as a single unit.

The authors did not recognize this upper Martinsburg sandstone along the series of section west to Doubling Gap except at Little Mountain. Lithologically, stratigraphically and faunally it appears to be the correlate of Bassler's Fairview sandstone in south-central sections but it is not traceable through. Therefore, the distinctive geographic name, Shochary sandstone, after the ridge in northeastern Berks County (Hamburg quadrangle) where it carries a Pulaski fauna and can be readily studied, is suggested.[3]

At Schuylkill Gap the Shochary sandstone underlies the Tuscarora sandstone. At the exposed contacts, the discordance is almost 90 degrees.

[3] This name has been checked and pronounced available by Miss Alice S. Allen, U. S. Geol. Survey, letter of November 25, 1938.

The Ordovician beds lying nearly horizontal meet the approximately vertical Silurian. The contact is concealed on the highway opposite a dam in the river, but on the Reading Railroad it is exposed twice in a cut near the same dam and again three-fourths of a mile west. The best exposure is on the Pennsylvania Railroad at the west side of the entrance to the Gap. On the highway *Arthrophycus* occurs almost at the base of the Tuscarora and not more than 10 feet above its concealed contact with the Shochary sandstone. The Tuscarora is the usual comparatively fine conglomerite, not the coarse, discolored, friable conglomerate so typical of the eastern Bald Eagle. On the west side of the Gap, where the Ordovician sandstones are somewhat shaly, it is inferred that they are near the base of the Shochary or close to the top of the Eden shale. Nothing resembling the red Juniata is present in this section. No identifiable fossils were found in the shaly Martinsburg or Shochary sandstone south of the contact.

The conditions at the Ordovician-Silurian contact on the Schuylkill are different from anything encountered to the west. Is this a fault contact? Arguments have been offered for and against such a proposition. Neither the red Juniata nor its basal member—the Bald Eagle—is present, but Upper Ordovician sandstones above the Martinsburg (Eden) shales are present. The Ordovician-Silurian relations display the greatest angular discordance recorded in the State. As will presently be described, the Bald Eagle conglomerate is thought to reappear farther east. For these reasons it is deduced that faulting may actually cut out the beds normally found immediately below the Tuscarora. It may be recalled that *Arthrophycus* occurs near the base of the exposed Tuscarora on the east side of the Gap. This fossil is seldom if ever found so low in the formation in the more western sections. Its presence therefore in its recorded position on the Schuylkill suggests that the lower part of the Tuscarora has been cut out by faulting.

LEHIGH GAP

Between the Schuylkill and the Lehigh rivers, sections observed across Kittatinny Mountain added no information. The west side of Lehigh Gap furnished nothing conclusive. The well-known exposures on the east side were restudied. A new interpretation of the sequence is offered. The exposed Martinsburg along the highway at the Gap entrance is sandy. One hesitates to suggest that it may be the Shochary until more detailed correlations can be made between the Slate Belt in Lehigh and Northampton counties and the less metamorphosed areas west of the Lehigh River. In all probability it is older than the Shochary. In these beds the senior author found graptolites too badly preserved for

identification. By analogy with other occurrences of these fossils they imply beds older than the Shochary. The overlying Silurian beds are exposed in railroad and highway cuts, but the Ordovician-Silurian relations are seen only on the Lehigh and New England Railroad. Between the Martinsburg and the overlying strata there is an angular unconformity of about 8 degrees. The first post-Martinsburg bed is a 3- or 4-foot conglomerate, coarse, rusty, poorly sorted. It consists of well-rounded pebbles in a ferruginous, sandy cement. Many of the phenoclasts are gray sandstone similar to the sandy Upper Ordovician beds. This conglomerate is so weakly cemented that it may be pulled down in chunks with a hand pick. It stands out in marked contrast to the overlying Tuscarora of hard, massive sandstones, quartzites, and conglomerites from which it is sharply separated only on lithology. The coarse conglomerate may not be, strictly speaking, typical Bald Eagle, but it is so decidedly unlike anything in any adjacent beds and so very like the Bald Eagle in most of its lithologic characters, its stratigraphic position, and its relations to sub- and superjacent formations that it seems certainly to belong to that member. This coarse stratum if not the basal conglomerate of the Tuscarora is more truly a persistent remnant of the Bald Eagle conglomerate member of the Juniata formation so well known to the west. Its presence here substantiates what has been suggested regarding the structure at the Schuylkill and the possible faulting out of the Bald Eagle in that section.

NORTHEASTERN SECTIONS

No additional data have been found in Pennsylvania east of the Lehigh River. At Little Gap, a newly improved road south over Kittatinny Mountain shows the Tuscarora with *Arthrophycus* common. The beds dip steeply south, their base hidden. At Wind Gap, exposures similar to those at Little Gap add nothing. A few small gaps east of there toward the Delaware River gave up no new facts. Swartz and Swartz (1931) reported that at the Delaware Water Gap the Tuscarora is not separable as a distinct unit from the rest of the lowest Silurian. It and the Clinton are together included under the name Shawangunk formation. The authors believe the base of the Shawangunk is hidden at Delaware Water Gap on both the Pennsylvania and New Jersey sides (Willard, 1938). Old slate quarries in the Martinsburg near the Gap indicate that the highest beds of that formation are not arenaceous. The oldest exposed Shawangunk is typical, fairly coarse, very hard conglomerate, sandstone, and quartzite beds. Among all that are exposed, no bed even remotely suggests the Bald Eagle. That there is an angular discordance between the Shawangunk and Martinsburg has long been

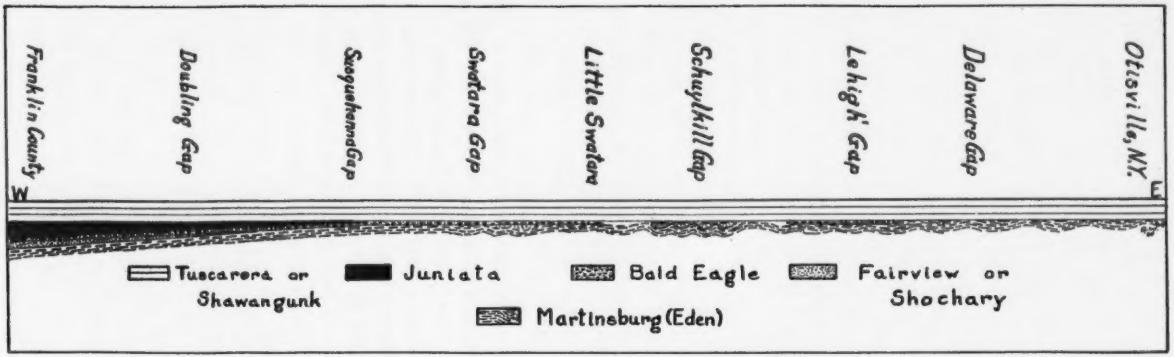

FIGURE 2.—*Generalized, east-west section across Pennsylvania*

To show the relations between the Tuscarora, Juniata red beds, Bald Eagle conglomerate and sandstone, Fairview and Shochary sandstones, and shaly Martinsburg. All thicknesses are necessarily drawn out of true proportions owing to excessive differences among the several units and the variations of individual units. The section is approximately 200 miles long.

inferred from their unconformable relations at the Lehigh Gap to the west and at Otisville, New York, on the east.

No new information was obtained from New Jersey. The senior author visited sections across Kittatinny Mountain and the isolated syncline of Green Pond Mountain in north-central New Jersey and nearby New York. He agrees with the findings of the New Jersey geologists (Lewis and Kümmel, 1915). The Ordovician and Silurian near Otisville, New York, have been often described, and their contact on the Erie Railroad figured. The Shawangunk rests on the Martinsburg with a divergence of dips of 7 or 8 degrees. There is conglomerate at the base of the Shawangunk, but nothing here can be assigned to the Bald Eagle or Juniata red beds. The Martinsburg at the contact is shaly, and it may be pre-Eden in age. In comparison, in a section which the senior author observed along the highway from Port Jervis to Middletown, New York, there is a conglomerate at or near the base of the Shawangunk which carries what appear to be fragments of slate or shale derivable from the Martinsburg, yet there seems no reason for calling it Bald Eagle. The highest observed Martinsburg here is sandstone with interbedded shale.

CORRELATIONS

Correlations of the Shawangunk and Tuscarora have been worked out by Swartz and Swartz (1930; 1931) who assign the basal Shawangunk or the Tuscarora to the lowest Silurian in Pennsylvania. F. M. Swartz (1934) following accepted usage has correlated the Juniata with the Queenston red shale of western New York, thereby admitting its age as Richmond. The Castanea sandstone, which overlies the Tuscarora in central Pennsylvania, Swartz ties in with the Grimsby sandstone near Rochester, New York. As the Grimsby is of late Medinan age (Goldring, 1931) the underlying Tuscarora should be also the equivalent of at least part of the Medinan (*i.e.*, in a restricted sense above the Queenston) of New York. Such a correlation has been substantiated by Swartz and Swartz, and Willard (1928) believed that the lower part of the Shawangunk in eastern Pennsylvania represents early Silurian time.

There seems no doubt that the red Juniata at least is the correlate of the Queenston red shale of the Niagara falls region. The New York Survey puts the Queenston in the lowest Silurian and calls the Oswego highest Ordovician. The typical Oswego overlies and intergrades with the Pulaski shale. The Pulaski in turn overlies the Frankfort (Table 1). The Oswego at Salmon Falls, New York, is reported to contain Lorraine fossils (Goldring, 1931), and there is no Oswego-Pulaski break in that State. This sandstone is therefore considered in New York to

TABLE 2.—*Summary of thicknesses*

Localities	St or Ssg	Oj	Obe	Of or Osh	Om and Or
Otisville, N. Y.	750	Ab	Ab	Ab?	P
Delaware Water Gap	1830	Ab	Ab	Ab	P
Lehigh Gap	250	Ab	3	?	P
Schuylkill Gap	400	Ab	Ab	500[1]	P
Little Swatara Notch	P	Ab	6–7	Ab	P
Swatara Gap	400	Ab	4–5	Ab[2]	P
Heckert Gap	P	Tr	?	?	P
Susquehanna Gap, east	P	10+	5+	Ab?	P
Susquehanna Gap, west	275	80	30	Ab	P
Sterretts Gap	P	100+	?	Ab	P
Doubling Gap	P	575	Tr[3]	Ab?	P
East Blue Mountain tunnel	956[4]	775	148	204	910+
West Kittatinny Mountain tunnel	484	774	168	246	921+
East Tuscarora Mountain tunnel	509	820	124	135	1183
McConnellsburg-Fort Loudon	270	400	150	300	1500±
McConnellsburg-Mercersburg	250	400	125	300	1500±
Kishacoquillas Gap	820	1590	300	425	1367
Bellefonte	400	1000	800	40[5]	1000
Tyrone	500	1200	900	40[5]	1100

[1] Thickness estimated.

[2] On Little Mountain, 2 miles SSE, the sandstone is at least 300 feet thick.

[3] To the NW on Conococheague Mountain, the senior writer determined 43 feet of Bald Eagle.

[4] Excessive owing to repetition through faulting.

[5] "Siliceous limestone" of Butts.

St=Tuscarora, Ssg=Shawangunk, Oj=Juniata exclusive of the Bald Eagle, Obe=Bald Eagle, Of=Fairview, Osh=Shochary, Om and Or=Martinsburg and Reedsville shaly beds respectively.

P=present, but thickness undetermined or unsatisfactory. Ab=Absent. Ab?=probably absent, but interval concealed. Tr=Trace.

Data are from writers' observations checked against or amplified by information principally from the publications of R. S. Bassler, Charles Schuchert, G. W. Stose, C. K. and F. M. Swartz, F. M. Swartz, Charles Butts, Butts and Moore, and County Reports of the Second Pennsylvania Geological Survey.

be the closing phase of Ordovician sedimentation. In Pennsylvania, Bassler (1919) and others referred certain beds to the New York Oswego because of their stratigraphic position below the red Juniata, correlate

of the Queenston, and above the *Orthorhynchula* zone in south-central Pennsylvania. This latter zone is in a sandstone which Bassler correlated with the Fairview of Ohio. The Oswego is said to equal the McMillan of Ohio. These correlations are summed up in Table 1. The authors cited their objections to the use of Oswego in Pennsylvania and stated their preference for the old name Bald Eagle for these beds or their correlates. Consequently, although the Bald Eagle as here used may be partly equal to the New York Oswego, it is now classified as the basal member of the Juniata formation.

Table 2 summarizes the known thicknesses of the Ordovician and Silurian units discussed in this paper. As the south-central Pennsylvania sections are evidently the most complete in the State, they may be adopted as a starting point to tabulate the Ordovician-Silurian sequences across Pennsylvania (Table 3).

UNCONFORMITIES

Tables 3 and 4 show the hiatuses in the Ordovician-Silurian sequence across Pennsylvania. (*See also* Figure 2.) These are sedimentary or tectonic. Bassler (1919, Fig. 2, p. 49) drew a disconformity between the Juniata and "Oswego" in "Maryland and neighboring states." Neither at the surface in south-central Pennsylvania nor in the tunnels have the authors verified this observation. None of the sections shows any break from the shales of Eden age into the Tuscarora. Therefore, it is supposed that the disconformity which Bassler recorded is south of Pennsylvania.

Not until one reaches the Susquehanna Gap is an interruption in the succession observed. Based on incomplete exposures in northern Franklin, Cumberland, and Perry counties, there is probably a hiatus below the Bald Eagle because the Fairview has not been identified. At the Susquehanna River, the Fairview sandstone (or its correlate, the Shochary) is absent. The Bald Eagle member of the Juniata disconformably overlies the shaly Martinsburg. There is no evidence of tectonic movement prior to the deposition of the conglomerate and sandstone. Eastward toward Swatara Gap the red beds of the Juniata drop out. Their disappearance is interpreted as a depositional break because of lack of evidence for any tectonic movement at this level. The Tuscarora and Bald Eagle are disconformable, but there is evidence of post-Martinsburg movement in the small discordance of dips between the Bald Eagle and the Martinsburg. The presence of this break is substantiated further by the absence at Swatara Gap of the "upper sandy Martinsburg," although there is no proof of faulting here. The sandstone is probably present, however, 2 miles to the southeast in Little Mountain. There

TABLE 3.—*Upper Ordovician-Lower Silurian sequences across Pennsylvania*

Franklin-Fulton counties	Bellefonte-Tyrone area	Doubling Gap	Susquehanna Gap	Swatara Gap	Little Swatara Notch	Schuylkill Gap	Lehigh Gap	Delaware Water Gap	Otisville, New York
Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Shawangunk	Shawangunk
Juniata	Juniata	Juniata	Juniata						
Bald Eagle*	Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle		Bald Eagle	?	
Fairview	Fairview	Fairview(?)				Shochary			
Martinsburg**	Reedsville**	Martinsburg	Martinsburg	Martinsburg	Martinsburg	Martinsburg	Martinsburg	Martinsburg	Martinsburg

* Bald Eagle has been called "Oswego" locally.
** Martinsburg shale or slate and Reedsville shale, of Eden age or older. The Fairview has been treated as uppermost Martinsburg in the text.

the heavy sandstone is capped by an outlier of Tuscarora and Bald Eagle. Such a marked difference in so short a distance indicates strong plication and erosion in pre-Bald Eagle time. So profound was the deformation that the late Ordovician sandstones were infolded among the shales and preserved at Little Mountain, but the whole sandstone sequence was planed off before the Bald Eagle was laid down at Swatara Gap.

TABLE 4.—*Structural relations*

S. C. Penna.	Susque. Val.	Swatara	Little Swatara	Schuylkill	Lehigh	Otisville
Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Tuscarora	Shawangunk
CONF.	CONF.					
Juniata	Juniata	DISC.	DISC.		DISC.	
CONF.	CONF.			Fault?		
Bald Eagle	Bald Eagle	Bald Eagle	Bald Eagle		Bald Eagle	UNC.
CONF.	DISC.	UNC.	UNC.		UNC.	
Fairview				Shochary		
Eden	Eden	Eden	Eden?	Eden	Eden(?)	Eden ±

CONF. = conformity; DISC. = disconformity; UNC. = unconformity.

At the Schuylkill the Bald Eagle is absent. The Tuscarora rests at right angles upon the Shochary sandstone. The absence of the Bald Eagle may be due to faulting. Such a supposition is substantiated by its reappearance at the Lehigh River where there is a small angular discordance between the top of the beds assigned to the Martinsburg and the base of the overlying Bald Eagle. The latter is in disconformity with the superjacent Tuscarora. The remaining sections in Pennsylvania add nothing.

At Otisville, New York, the basal Shawangunk rests in angular discordance upon shaly Martinsburg. The sequence is not analogous to that at the Schuylkill for there is no reason to suppose that the Bald Eagle ever extended so far east, nor is there proof of the absence of any of the basal Shawangunk (Tuscarora) formation as seems to be the case at Schuylkill Gap. No faulting is recognized at Otisville, but the two hiatuses to the west—the one between the Bald Eagle and Tuscarora and the other between the Bald Eagle and the Martinsburg—have merged. The situation can be carried even a step further in north-central New Jersey where the Green Pond conglomerate, acknowledged correlate of the Shawangunk, rests upon pre-Martinsburg limestone (the Kittatinny) or in

nonconformity upon the pre-Cambrian crystalline rocks. The entire Martinsburg may be absent, but its occurrence to the west and the presence of the "Hudson schist" (Lewis and Kümmel, 1915) to the east suggest, if the latter be its correlate, that the shale once was present in the Green Pond Mountain region.

From west to east between the tunnel sections and the Susquehanna River, first the Fairview sandstone drops out; next, continuing east of the Susquehanna, the Juniata red beds disappear; finally, the Bald Eagle conglomerate vanishes east of the Lehigh River. In some eastern sections the Shochary sandstone appears at that part of the sequence vacated by the Fairview sandstone, though it is not recognized in the most eastern exposures.[4]

TACONIC DISTURBANCE

The authors believe that the Taconic Disturbance affected eastern Pennsylvania at least as far west as the Susquehanna Valley. This conclusion is based upon several lines of evidence.

The local absence of post-Eden sandstones at Susquehanna Gap and elsewhere where the Martinsburg shale and the Bald Eagle are in disconformity is no chance occurrence. It implies folding followed by erosion. The absence of these sandstones from the Susquehanna Valley suggests unstable conditions that may be an expression of Ulrich's Harrisburg axis (Ulrich, 1911). The parallelism of the Bald Eagle conglomerate and the shale of Eden age at the Susquehanna Gap may indeed be fortuitous, but this location should be near the western limit of any possible disturbance. The Fairview sandstone and higher formations are all conformable and presumably completely developed in the south-central exposures and in the tunnels. Eastward from the Susquehanna River angular unconformity is general beneath the Bald Eagle or, where that member is absent, the Tuscarora or Shawangunk. One section may be an exception—that on the Schuylkill—where there is faulting. From east to west the sections exemplify the geologic axiom that an unconformity traced far enough in the right direction passes over into a disconformity and then into conformity. The date of the Taconic Disturbance in Pennsylvania is fixed. The tectonic break is beneath the Bald Eagle—that is, it is chronologically pre-Richmond. Conversely, the youngest beds affected by the folding are of Pulaski age.

[4] To those familiar with the stratigraphic problems of the Slate Belt of Northampton and Lehigh counties, the question may arise as to whether or not the Shochary sandstone is the equivalent of the sandy member of the Martinsburg slate (*cf.* Behre, 1933). This the writers are not prepared to discuss nor shall they be until studies in progress by B. L. Miller, Freeman Ward, J. R. Moseley, and the senior writer shall have advanced farther.

The Appalachian Revolution, too, left its imprint on the sections but it involved entire sequences. It was at this later time that the Martinsburg and Shawangunk were uptilted as a whole, and it may have produced movement at certain contacts. If the Ordovician-Silurian contact on the Schuylkill is a fault, that structure is of Appalachian rather than Taconic age. Had the Appalachian Revolution, as some suggest, thrust the Ordovician beneath the Silurian, why were no similar thrusts produced among the Silurian, Devonian, Mississipian, and Pennsylvanian systems of eastern Pennsylvania? How, except by an interval of late Ordovician folding and peneplanation, is it possible to explain such a great syncline or succession of synclines of late Ordovician sandstones downfolded into older shales, then beveled off, and finally overspread by the Tuscarora sandstones and conglomerates as is recognized in northern Berks County?

ORDOVICIAN-SILURIAN BOUNDARY

Locally, the question of the Ordovician-Silurian boundary appears to be whether we accept interruption of sedimentation or invasion of a new facies of sedimentation as the stratigraphic key to the systemic boundary. For example, in the Susquehanna River section the Ordovician-Silurian separation might be made between the Martinsburg and the Bald Eagle solely upon the physical evidence of an interruption of sedimentation. Again, it might be argued that the boundary be designated as the base of the red Juniata in that the latter marks the incursion of a new facies of sedimentation. Through analogy with the sedimentary cycles of the Silurian, Devonian, and Mississippian systems in Pennsylvania, it would seem logical and consistent to assign the red beds to the top of the Ordovician rather than to the base of the Silurian. On other evidence, the Ordovician-Silurian line is traced from tectonic data.

Fortunately, sections east of Harrisburg supply pertinent facts. Based upon tectonic movement, the boundary can be drawn there at only one level, the bottom of the Bald Eagle, or, where that member drops out, the base of the Shawangunk. Stated conversely, a tectonic intersystemic break may be drawn only above the shaly Martinsburg, the Fairview, or Shochary, depending upon which is present beneath the unconformity, because all three were involved in the Taconic folding, whereas no succeeding units were so affected. Upon such reasoning the Juniata including the Bald Eagle should be Silurian. The New York stratigraphers call the Oswego late Ordovician. Since the Bald Eagle is not the precise correlate of the New York Oswego, however, the authors assign it to the basal Juniata. As such it might be interpreted as basal Silurian conglomerate.

Let us suppose an orogenic movement (Taconic Disturbance) followed by peneplanation occurred about middle Maysville time but that it never extended west of eastern Pennsylvania. The weak shales and the Shochary sandstone of the Martinsburg might conceivably suffer very rapid erosion. The Bald Eagle probably is continental only in part. Continental beds of such antiquity are usually red. Later ones may or may not be that color. Compare the red Catskill with the gray Pocono. In the Ordovician and early Silurian there probably was insufficient land vegetation to supply the necessary carbon to reduce the ferric iron of the sediments to a ferrous state. We assign the Bald Eagle to the basal Juniata. It marks a change from marine to continental conditions in central Pennsylvania. In these sections it is thick and may contain red beds. In south-central sections it is transitional with overlying and underlying formations but remains barren and is intermediate between the marine, fossiliferous Fairview sandstone and the continental, barren, red Juniata.

Resumed uplift unaccompanied by folding in the east closed Maysville time. Active, terrestrial erosion recommenced; the succeeding Bald Eagle and Juniata red beds spread westward and northwestward over the shales and sandstones of the Martinsburg and Reedsville. These continental red sediments were syngenetically colored through derivation from red regolith accumulated on the Martinsburg and older (*cf.* New Jersey) beds during late Maysville time following the Taconic Disturbance. It might be supposed, as was suggested by Willard (1928), that the Tuscarora, Shawangunk, Juniata, and Bald Eagle are in part or wholly the material eroded directly from the east and laid down to the west and northwest immediately following the Taconic Disturbance. Our present understanding of the Bald Eagle, its distribution, and relations to succeeding and underlying beds blasts this theory, since we cannot by such an explanation account for the wide distribution of the Bald Eagle conglomerate across the beveled edges of the Martinsburg shale and sandstones. We have no present evidence as to the whereabouts of the debris removed directly after the Taconic orogeny. The "transitional" contact between the Juniata and Tuscarora in south-central and central regions marks the change from continental offlap to marine onlap. It is a cryptic disconformity which passes into an apparent disconformity eastward. On one hand, it resembles a diastem, on the other it is a true and clearly marked hiatus in sedimentation between the deposition of the red Juniata and Bald Eagle and the Tuscarora or Shawangunk (*cf.* Tables 3 and 4).

Where the Ordovician-Silurian line will be drawn eventually is a matter of perhaps smaller consequence to the stratigrapher than is the question of where the Ordovician cycle of sedimentation ended and that of

the Silurian began. This cyclic or sedimentary boundary may be drawn between the Juniata and Tuscarora or their members or correlates as marking the cessation of continental sedimentation which terminated the older cycle and the reincursion of the sea which initiated the younger cycle. This is analogous to the interpretations of the Silurian Bloomsburg, Devonian Catskill, and even the Mississippian Mauch Chunk continental, dominantly red facies in Pennsylvania. By this analogy the Ordovician-Silurian boundary will be drawn at the base of the Tuscarora or its correlate, the base of the Shawangunk. From the standpoint of the date of the Taconic Disturbance, the tectonic boundary must be drawn beneath the Bald Eagle and red Juniata. This places them in the Silurian. In this it agrees with those workers who, upon paleontologic evidence, assign the Richmond to that system. Pennsylvania is too small an area upon which to base so important a decision. The final verdict (if indeed one is necessary) must take into consideration the recorded conditions over eastern North America and Europe.

CONCLUSIONS

The authors have discussed the Ordovician-Silurian relations in Pennsylvania, particularly as known along the first range of mountains north of the great lowland belt of the Ordovician limestones and shales and slate. They have cited known facts and previous interpretations and to these added their own observations, deductions, and reinterpretations. The conclusions are:

(1) There is an unconformity at the base of the Bald Eagle extending from the Susquehanna River, if not farther west, eastward. This may cut out locally and more or less entirely the Fairview or Shochary sandstones of early Maysville (Pulaski) age. East of the Susquehanna River this hiatus is everywhere a tectonic unconformity in which the dip differences vary from 5 or 6 to approximately 90 degrees.

(2) There is a second, younger hiatus between the Bald Eagle and the Tuscarora where the red Juniata disappears east of the Susquehanna Valley. No measurable discordance of dips was found at this disconformity; it is of sedimentary rather than tectonic origin.

(3) In the extreme east both the Bald Eagle and the red Juniata are missing, and the most profound break of all occurs through a merging of the two hiatuses. The basal Shawangunk rests unconformably upon folded and eroded Martinsburg shale. This break evidently had a combined tectonic and sedimentary origin.

(4) There is insufficient evidence for correlating with the New York Oswego the conglomerates and sandstones in Pennsylvania which have sometimes been given that name. Therefore, they are referred to by the

revived name, Bald Eagle. Upon stratigraphic and structural evidence, the Bald Eagle is considered the basal member of the Juniata formation.

(5) The Taconic Disturbance in Pennsylvania affected the stratigraphic sequence through beds of Pulaski age but not those assigned to

TABLE 5.—*Summary of events*

CHRONOLOGY	EVENTS
Medinan	Tuscarora-Shawangunk deposition in invading sea
Richmond	Bald Eagle conglomerate and sandstone and Juniata red beds deposited to west and northwest as reworked, transported, residual soils derived from land to the east and southeast, chiefly continental facies
Richmond-Maysville interval	Uplift by tilting, unaccompanied by folding, of the eastward landmass; rejuvenation of streams
Late Maysville	Quiescence; accumulation of red regolith over peneplaned but exposed Martinsburg and older formations to the eastward
Middle Maysville	Taconic orogeny, folding, uplift; followed finally by peneplanation growing progressively more deeply penetrating from the Susquehanna Valley eastward
Early Maysville	Deposition of the Fairview and Shochary sandstones to the west and east respectively, perhaps in separate basins, possibly connected by subsequently eroded, similar beds. This marked the closing events of Martinsburg (or Reedsville) sedimentation and ended in the withdrawal of the sea.
Eden and older	Deposition of Upper Martinsburg and Reedsville shales

the Bald Eagle and red Juniata. This movement was inoperative west of the Susquehanna Valley so far as known.

(6) Based upon the interpretation of the sedimentary cycle, the Ordovician-Silurian boundary in Pennsylvania separates the Tuscarora or Shawangunk from the underlying strata, whether these are Juniata, Bald Eagle, or Martinsburg. Tectonic evidence indicates that the Ordovician-Silurian line is at the top of the Martinsburg (Eden shale or one of its sandstone members—the Fairview or Schochary). By this procedure, the Bald Eagle and Juniata become basal Silurian. Table 5 sums up the chronology of the late Ordovician and early Silurian events.

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